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METALLURGICAL COALS IN CANADA: RESOURCES, RESEARCH, AND UTILIZATION

JOHN T. PRICE AND JOHN F. GRANSDEN

CANMET

Canada Centre for Mineral and Energy Technology

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JOHN T. PRICE and JOHN F. GRANSDEN
Combustion and Carbonization Research Laboratory

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METALLURGICAL COALS IN CANADA: RESOURCES, RESEARCH, AND UTILIZATION

John T. Price and John F. Gransden

Abstract

Canada has a vast metallurgical coal base located mainly in the Provinces of British Columbia and Alberta in the west and Nova Scotia in the east. Large mines, efficient rail transportation and port facilities, and good coking coal properties at competitive prices have allowed Canada's metallurgical coal exports to double in the last 12 years to 22 million tonnes.

Western Canadian and eastern Canadian coals are quite different as a result of their different geological histories. The Cretaceous western Canadian coals were formed about 100 million years ago in swamps but, unlike the Carboniferous coals from eastern North America, have generally matured in a non-marine environment. The stresses that occurred during the formation of the mountains in western Canada have brought the coals to the surface, often in faulted, folded, or steep seams. The resulting coals range from high-volatile to low-volatile bituminous in rank and generally are friable. They have more inherent ash and semifusinite, and less sulphur and alkalis than corresponding Carboniferous coals. Their unusually low Gieseler fluidity and dilatation properties make these test methods, at best, doubtful in grading Cretaceous coking coals.

Individually, western Canadian coals make strong cokes with excellent coke strength after reaction (CSR) properties because of the low basicity of their ash. Removal of mineral matter, and high bulk density charging of coke ovens significantly improves their coke quality. The MVB coals can be added to eastern North American binary blends to bridge the fluid temperature ranges of the component coals, to reduce coking pressures and to improve CSR properties. Weak and non-coking coals from western Canada can be used in conventional cokemaking, partial briquetting, pitch additives, or form coke processes using pitch binder. Pitch enhances the caking properties of these coals and improves coke properties. Strong formed coke can be made by carbonizing briquets made from oxidized western Canadian coals without the use of binder. Weak and non-coking coals could also be used in other metallurgical processes such as direct ironmaking and coal injection into blast furnaces.

Coals from Atlantic Canada are Carboniferous and were formed 200 million years prior to the Cretaceous coals from western Canada. Coking coal from Nova Scotia has good blending properties and ideally complements the properties of the western Canadian coals to make strong cokes. It is hvA bituminous in rank, has low ash but high sulphur and vitrinite contents, and very high fluidity and dilatation properties. It can be used effectively in preheating processes. Char or petroleum coke can be incorporated into coking blends containing this coal to make strong coke. It is a very good binder coal in hot briquetting formed coke processes because of its high caking properties.

Details and results of CANMET investigations of Canada's metallurgical coals are discussed.

LES CHARBONS MÉTALLURGIQUES AU CANADA: RESSOURCES, RECHERCHE ET UTILISATION

John T. Price et John F. Gransden

Résumé

Le Canada possède de vastes couches de charbon métallurgique situées principalement dans les provinces de la Colombie-Britannique et de l'Alberta dans l'Ouest et de la Nouvelle-Écosse dans l'Est. De nombreux facteurs tels que des mines de houille importantes, des installations ferrovières et portuaires permettant un transport efficace du produit exploité, et un charbon ayant de bonnes propriétés de cokéfaction à des prix compétitifs, ont permis au Canada de doubler ses exportations de charbons métallurgiques au cours des douze dernières années.

Les charbons de l'Ouest et de l'Est canadien diffèrent beaucoup en raison de leur histoire géologique différente. Les charbons crétacés de l'Ouest ont été formés il y a 100 millions d'années dans des marais, mais ont mûri en général dans un milieu non marin contrairement aux charbons carbonifères de l'Est de l'Amérique du Nord. Les tensions produites au cours de la formation des montagnes dans l'Ouest canadien ont fait monter le charbon à la surface souvent dans des couches faillées, plissées ou fortement inclinées. Le rang de ce charbon va de bitumineux à haute teneur en matières volatiles à bitumineux à faible teneur en matières volatiles. Ces charbons sont généralement friables et semifusinites avec une teneur inhérente en cendres et ont une faible teneur en soufre et en alcali en comparaison avec les charbons carbonifères correspondants. Enfin, les résultats obtenus des méthodes d'essais visant à classifier les charbons cokéfiants sont douteux tout au plus en raison de la faible fluidité de Gieseler et des propriétés de dilatation inhabituelles de ces charbons.

Les charbons de l'Ouest canadien pris individuellement produisent des cokes résistants avec d'excellentes propriétés de résistance après réaction (CSR) vu le faible indice de basicité de leurs cendres. L'extraction de la matière minérale et la densité élevée de la charge d'alimentation des fours à coke améliorent considérablement la qualité du coke. Les charbons BMV peuvent être ajoutés aux mélanges binaires provenant du nord-est américain dans le but d'établir un lien entre les gammes de température du fluide des charbons constituants du mélange, de diminuer les pressions créées pendant la cokéfaction et d'améliorer les propriétés CSR. Il est possible de se servir des charbons pauvres et non cokéfiants de l'Ouest canadien pour les procédés classiques de cokéfaction, le briquetage partiel, comme additifs de brai ou lors des procédés de cokéfaction utilisant le brai en tant qu'agglomérant. Un coke résistant peut être produit en carbonisant des briquettes fabriquées sans agglomérant à partir des charbons oxydés de l'Ouest canadien. Les charbons pauvres et non cokéfiants peuvent aussi servir à d'autres procédés métallurgiques tels que la fabrication directe du fer et l'alimentation des hauts fourneaux.

Les charbons provenant de l'Est canadien sont carbonifères, et ont été formés 200 millions d'années avant les charbons crétacés de l'Ouest canadien. Les propriétés des charbons cokéfiants provenant de la Nouvelle-Écosse font qu'ils se prêtent bien aux mélanges et s'avèrent un complément idéal aux charbons de l'Ouest canadien lors de la fabrication de cokes résistants. Le charbon de l'Est est classé dans le rang des charbons bitumineux "A" à haute teneur en matières volatiles ayant une faible teneur en cendres, une haute teneur en soufre et en vitrinite ainsi que des propriétés élevées de dilatation et de fluidité. Ces charbons peuvent être utilisés aussi de façon efficace dans les procédés de préchauffage. L'addition de produits de carbonisation ou de coke de pétrole aux mélanges de coke contenant du charbon de l'Est permet d'obtenir un coke résistant. De plus, ce charbon est un excellent agglomérant pour les procédés de fabrication de coke en briquettes en raison de ces propriétés agglutinantes élevées.

Le présent rapport présente en outre les détails et les résultats obtenus des études sur les charbons métallurgiques canadiens réalisées par CANMET.

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INTRODUCTION

Canada is a major exporter of good coking coals. Since 1975 Canada's coking coal exports have doubled in quantity and in 1986, Canada exported 21.5 million tonnes of coking coal, about 82% of Canada's coal exports. Japan continues to remain the largest market, representing about 73% of total sales in 1986. However, the trade pattern has changed over the last 12 years and now more coal movements are made to Korea, Taiwan, Latin America, and Europe (1). Only about 3% of Canada's total coal production is used within Canada's metallurgical industry because steel plants in central Canada traditionally import Appalachian coals from the eastern United States (2).

About 90% of metallurgical coal is used by the steel industry for making iron. Steel producers' prime objective with coal is to make high-strength coke to fuel blast furnaces. The coals must be converted to metallurgical coke by carbonization in heated refractory chambers called coke ovens. Coke is the solid carbon residue containing some mineral matter that remains from the destructive distillation of the coal in these chambers. Metallurgical coke serves as the energy source for producing iron and steel by burning at the tuyeres at the base of the blast furnace to form carbon dioxide. The coke further reacts with this carbon dioxide and moisture injected into the blast furnace to produce the carbon monoxide and hydrogen reductants that convert iron oxide ores to iron. Coke also provides a permeable support for the blast furnace burden materials to allow for uniform reduction of the iron ores.

Good metallurgical coke must have two basic properties. Firstly, it should be of high strength and resistant to chemical attack so that it does not degradate during its descent through the blast furnace. This ensures that the blast furnace burden remains permeable and allows reducing gases to pass uniformly through the burden, improving both the blast furnace efficiency (fuel rate) and iron productivity. Secondly, coke should contain a minimum of foreign compounds that: contaminate the iron (sulphur, phosphorus); add to slag formation and therefore increase flux requirements and fuel consumption (silica, alumina); cause operating problems in the blast furnace (alkalis, titania). These compounds, with the exception of sulphur, are mainly components of coal ash.

High-strength coke is made conventionally by crushing cleaned bituminous coals (by definition those that demonstrate softening or plastic behaviour at temperatures between 350° and 500°C) to about 3 mm and carefully blending them to give an overall volatile matter content, inert content, thermal rheology, ash content, and chemistry meeting very tight specifications. The blend containing about 6-8% moisture, with some diesel oil added to control its bulk density, is charged to a coke oven about 400-460 mm wide (holding typically 17 tonnes of coal) and coked for about 18 h. As a result of the stringent specifications placed on metallurgical coke, good coking coals are premium coals and command the highest market price. Poorer quality coals can be used in conventional coke ovens to make metallurgical coke but they require specialized technologies (e.g., partial briquetting, preheating of coal) that generally involve operating coke ovens at higher coal bulk densities and different coking rates. Although not used in Canada, these and other new technologies are being used in Japan and other Pacific Rim countries and impact on the types of coals marketed in these countries.

Canada's coking coals have unique properties, advantages and problems in comparison to other coking coals from around the world. They can be used solely or as a component of coal blends. This paper describes the properties of Canadian metallurgical (coking) coals and the results of laboratory, pilot plant, and industrial trials sponsored by CANMET and the Canadian Carbonization Research Association on Canadian coking coals.

LOCATION AND GEOLOGICAL SETTING OF CANADA'S MAJOR METALLURGICAL COAL RESOURCES

Canada's bituminous metallurgical coal resources are at present estimated to be 2030 megatonnes of recoverable coal. The resources are found primarily in three provinces: Nova Scotia, Alberta, and British Columbia (Fig. 1) with 133, 254, and 1643 megatonnes of recoverable coal, respectively (3). Details of mining operations in these provinces and analyses of the coals produced are given in Appendix A and B, respectively.

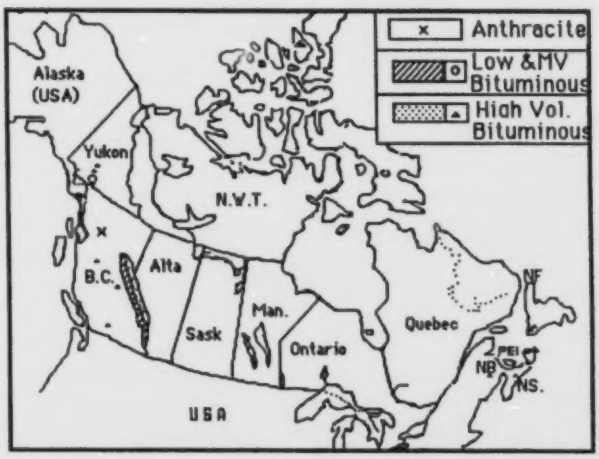

Fig. 1 - Canada's metallurgical coal deposits

EASTERN CANADA

The first printed report on Canada's coal resources was written by the Governor for France of

Cape Breton Island in 1672 and describes the coal of the Atlantic region. Today, the Sydney Coalfield on Cape Breton Island is by far the most important coalfield in Nova Scotia and contains 11 major seams. The metallurgical coals from Atlantic Canada are of carboniferous age, being formed 300 million years ago during the Westpahalian C and D epochs, during which the main coal deposition in Europe also took place. The Sydney Coalfield forms part of the offshore carboniferous basin that extends to Newfoundland and occupies some 36 000 square km (4,5). The high pyrite content, as well as the low inertinite maceral content, suggests these coals were formed from peat swamps with a marine cover (6). In Cape Breton, basically all the coal seams outcrop on shore and dip seaward at gradients ranging from 5 to 30°. Three seams - the Harbour, Phalen, and Hub seams - are currently being mined by the Cape Breton Development Corporation. Coal from the Harbour and Phalen seams is of metallurgical grade and is high-volatile bituminous "A" with low-ash but high-sulphur content. The pyritic sulphur is removed in a coal preparation plant using heavy media cyclones and froth flotation cells. The lower specific gravity fractions (up to 1.3 S.G.) are combined to make a metallurgical coal with 3.0% ash and 1.2% sulphur. A middlings product from the process is sold on the thermal market. The metallurgical coal is considered an excellent component in coking blends because of its high thermal rheological properties. With a location on tide water, coal from Sydney can be easily shipped to customers in Ontario, Europe, and South America.

WESTERN CANADA

High-rank coking coals occur in large deposits in the Rocky Mountain and foothills regions of Alberta and British Columbia stretching from the U.S.A. border to the Yukon. Such late Jurassic to early Tertiary coals would normally be lignitic or subbituminous in rank, as in the plains areas of Alberta and Saskatchewan. The Rocky Mountain coals have undergone quite a different coalification regimen than similarly ranked Carboniferous/Permian coals from eastern and central North America or elsewhere in the world. Unlike most Appalachian coals, these coals were generally formed in peat swamps under a nonmarine cover that maintained the acidic nature of the bog and with periodic oxidizing conditions that resulted in coals having higher inertinite with reduced volatile matter contents, and higher kaolinite and quartz with reduced pyrites in the ash (6). These coals were metamorphosed to ranks similar to the Carboniferous coking coals that are about 200 million years older; this is perhaps attributable to the effect of the Tertiary Laramide Orogeny (7, 8), although some geologists have argued that the metamorphism is almost entirely thermal and not caused by tectonic stresses (9). The thrust force exerted by the Orogeny on the flat seams under a sedimentary cover of several thousand feet brought coal seams closer to the surface from their original burial location, but resulted in folding and faulting that produced considerable irregularities, discontinuities, and highly pitched seams; all of which complicate seam correlation, mine planning, engineering, and development. The shearing within coal seams has made the coal very friable, resulting in a particle size consist significantly finer than from other operations in the world. The fine nature of the coals contributes to the difficulty in obtaining optimum wash yields and creates special handling, preparation, and drying problems.

Coal degradation may now be predicted by the test procedures developed in Australia (10) and Canada (11). Using a test called the delta P method, which measures the initial desorption of methane gas from coal, CANMET scientists have related the amount of -0.6 mm material and the coal friability index to the desorption properties of the coal. CANMET, in a study of seam depth, has also shown that the abnormal size consist of the Rocky mountain coals is largely attributable to the sheared seam structure, but in-situ oxidation is also a contributing factor (12).

Unlike the Sydney Coalfield, which is located on tidewater, the coking coals of western Canada are located in mountainous regions some 1100 km of very difficult terrain from Pacific ports, near Vancouver and Prince Rupert. The coalfields are even further from the steel industries of central Canada and only limited coal can be marketed in this region due to transportation costs. Improvement of the railway systems with unit trains and development of a port at Thunder Bay have reduced transportation costs, but the economics of long-distance transport of coal to export ports is probably the major obstacle facing western coal producers in providing competitive products.

Alberta Metallurgical Coalfields

The Cadomin-Luscar Coalfield located in the foothills of the Rocky Mountains southeast of Hinton is Lower Creataceous in age. The Jewell seam is of major commercial importance with a true thickness of 8-14 m, and is found near the middle of the 435 m thick Luscar Group formation (3,13). Coal rank is from high- to low-volatile bituminous. Mines in the area include Cardinal River Coals Ltd. and Gregg River Coals Ltd.

The Smoky River Coalfield about 100 miles to the northwest is within the middle part of the Luscar Group Formation and is also of Lower Cretaceous age. Eleven coal seams ranging in thickness from 0.6 to 7.9 m have been identified. Three seams (No. 4, 10, and 11) that are of commercial significance are being mined using surface and underground methods by Smoky River Coal Ltd. The coal is low-volatile bituminous in rank (3).

British Columbia Metallurgical Coalfields

The Crowsnest Coalfield is located in the southeast corner of the province in the East Kootenay Mountain region and has been commercially mined since the completion of the lower limb of the Canadian Pacific Railway and the opening of the Michel Mine in 1898. The coal, which ranges from low- to medium-volatile bituminous in rank, occurs in multiple seams within the Kootenay Formation of Lower Cretaceous-Upper Jurassic age.

There are 14 seams of economic significance in the vicinity of the Westar Mine near Sparwood. No. 10 seam is about 11 m thick and provides the bulk of coal production primarily from surface operations.

The Elk Valley Coalfield is located just north of the Crowsnest Coalfield and is of major economic significance, with three mining companies operating surface mines in the area. Coal seams fall within the Kootenay Formation, of Lower Cretaceous age, and range upward in sequence from low- to high-volatile. In the vicinity of the Fording River Mine, up to 11 seams are mined with thickness between 1.5 and 20 m. At Westar's Greenhills Mine, located 10 km south, 29 seams have been identified, the bulk of production coming from four seams with thicknesses from 5 to 16 m. At the Line Creek Mine, near the southern end of the coalfield, seven seams are mineable, ranging from 3 to 13 m (3).

The Peace River Coalfield is located in the Rocky Mountain foothills of northeastern British Columbia. The principal coal formations are found in the Gething Formation and the Gates Member of the Commotion Formation. Two mines have recently commenced production in this coalfield: the mine of Quintette Coal Ltd. and the Bullmoose Mine of Teck Corporation. At the Quintette mine the more economically significant coal measures occur within the Gates Member of the Commotion Formation where seams A,B,C,D,E,F, G/I, and K have been identified. Coal rank is within the medium-volatile bituminous range.

Coal Preparation

Coals from western Canada generally have low sulphur, chlorine, and other contaminants. Preparation is primarily a matter of cleaning to reduce the ash content without the complications of also removing trace elements. However, coal cleaning does require complex plants because of the fine mean particle size and relatively difficult cleaning characteristics of the coals. Although it is possible to achieve a 10% ash product from coals typical of eastern North America or western Europe by using a conventional jig with a separation density of 1.80, most western Canadian coals require accurate heavy medium processes and a separation density of less than 1.50 to achieve an equivalent 10% ash product. Preparation plants in western Canada generally use heavy media vessels or heavy media cyclones (1.45 -1.55 S.G.) to treat all coal coarser than 0.6 mm. Fines are beneficiated using both water-only washing cyclones and froth flotation cells.

With coal degrading further during the preparation operations, much higher fines (0.6 mm x 0) contents than the 25% considered typical for similar rank coals from other parts of the world are encountered at several preparation plants in western Canada. Consequently, water-only washing cyclone circuit capacity in western Canadian preparation plants is used far more extensively than elsewhere to treat the 0.6 x 0.15 mm coal. CANMET has developed an improved water cyclone, the Tri-Cone, to treat the fines and continues to do studies to optimize circuitry for these systems. Coal of size 0.15 x 0 mm passes to the froth flotation cells and the cleaned product is skimmed from the cells. The fines are dewatered in most plants using screen bowl centrifuges and/or rotary vacuum disc filters. The total product is dried at most preparation plants using fluid bed dryers (14).

The specifications and the size consist of a typical western Canadian clean coal product are given in Table 1.

Table 1 - Typical specifications and size consists of clean coal from a western Canadian preparation plant

Specifications	
Ash	9.0±0.5%
Moisture	<8.0%
FSI	>5
Sulfur	≤0.5%
Size fraction (mm)	(wt %)
+ 50	2.2
50-25	4.7
25-13	8.1
13-6	9.5
6-3	18.3
3-0.6	21.7
0.6-0.15	20.5
-0.15	15.0

CONVENTIONAL COKEMAKING

PILOT-SCALE INVESTIGATIONS

Metallurgical Coke Quality From Single Canadian Coals

High-quality coke for the blast furnace should be strong and be a relatively pure source of carbon. Coke purity is measured by various chemical analyses, while coke strength is traditionally evaluated throughout the world by standardized tumbler tests that measure the amount of coke retained on a certain-sized screen after tumbling in a standard tumbler drum. The ASTM tumbler test is used almost exclusively in North America to evaluate coke strength; the JIS and ISO tests are used in Japan and Europe, respectively. Desirable properties for blast furnace coke are given in Table 2. CSR is a measure of coke strength after reaction with CO_2 at 1100°C for 2 h (15,16,17,18).

With the exception of the CSR specification, developed by Japan's Nippon Steel Corporation, the above specifications are typical of Canadian steel plants. Variations beyond these target limits increase the coke used per tonne of hot metal, cause operating problems in the blast furnace, or give unacceptably high concentrations of impurities in the hot metal. Specifications on coke strength have changed in recent years. Ten years ago steel plants in North America strived for ASTM stability factors of 55, but now coke stabilities of 58 are the norm (19). In Japan, cokes with ash levels of 10-11.5% are produced at many

steel plants. Coke strength is measured in terms of the JIS drum tests and the coke strength after reaction (CSR) test. Japanese lower limits for the DI^{30}_{15} and the CSR index for high-quality cokes to be used in their large blast furnaces are about 93 and 55-57.5, respectively (20). Every 1% decrease in the CSR from the value of 57.5 increases coke consumption by about 1.45 kg/tonne of hot metal produced.

The best method of evaluating a coking coal is to run a full-scale industrial trial, analyze the coke produced, and evaluate its behaviour in the blast furnace. However, these tests are costly and a number of laboratory methods are usually used as a preliminary means to evaluate the quality of coking coals. These include chemical analyses, petrographic analysis, and thermal rheological measurements (FSI, Gieseler plasticity, dilatation, etc.). Typical properties of a coal or blend of coal that would produce a coke within target specifications are given in Table 3. The caking properties and mean reflectance ranges are derived from a number of models that have been developed (primarily for carboniferous coals) to predict coke quality. These models will be discussed in a later section.

Pilot-scale coke oven tests are the most reliable method to assess coal for coking purposes. Carbonization and heat transfer in pilot ovens simulate industrial practice since pilot test ovens have similar widths to industrial ovens and coals can be carbonized at the same bulk density, size consist, and heating rate as industrial operations. About 200 kg of blast-furnace-like coke is generated by these ovens and can be evaluated in the same manner as industrial coke by chemical, microscopic, tumbler and reactivity methods. At CANMET, round-robin investigations in test ovens have been conducted with both Canadian and Japanese steelmakers to compare test oven coke with that made industrially (21,22,23). As a result, it can be stated with some confidence that a coke made from a given coal in CANMET's test ovens will produce a test sample approaching the same quality as would be produced by industry.

Table 4 gives the results of recent coke oven tests done at CANMET laboratories on the eastern Canadian metallurgical coal and five typical western Canadian production coals of ranks varying from high-volatile A to low-volatile bituminous. Carbonization was done in a 460 mm wide oven with

Table 2 - Desired properties for metallurgical coke

Coke Property	Cdn Steel Plants		Japanese Steel Plants	
Ash.....	%	8.0	10-11.5	(upper limit)
Volatile matter.....	%	1.0		(upper limit)
Sulphur.....	%	0.7	0.75	(upper limit)
Alkali oxides.....	%	0.2		(upper limit)
Phosphorous pentoxide.....	%	0.27		(upper limit)
Coke stability (ASTM).....		55-60		(lower limit)
JIS $DI^{30}/15$.....			93	(lower limit)
CSR.....			57.5 *	(lower limit)
RSI.....			68.0**	(lower limit)

Specifications of: * Nippon Steel Corporation, ** Kobe Steel

Table 3 - Properties of a coal or blend likely to produce coke within target specifications

Grade	%
Ash	6-8
Volatile matter	28-31
Sulphur	0.8
Alkali oxides	0.19
Mean max reflectance	1.10-1.25
Caking Properties	
FSI	6
Gieseler plasticity	200-1000 ddpm
Dilatation	50-140
Operating and Test Oven Properties	
Maximum wall pressure	10-14 kPa
Expansion/contraction	-6

Table 4 - Analyses of Coals and resultant cokes made from an eastern hv coal and five western Canadian coals in CANMET pilot-scale tests ovens

	COAL PROPERTIES					
	Nova Scotian	Western Canadian Coals				
Coal Charge Properties	hvA	Coal A (hv)	Coal B(mv)	Coal C(mv)	Coal D(mv)	Coal E(lv)
Mean reflectance Ro.....%	0.99	0.90	1.01	1.27	1.28	1.62
Volatile matter, db.....%	36.0	31.9	26.5	21.7	21.6	17.4
Ash, db.....%	3.0	6.1	7.1	9.6	9.3	7.2
Sulphur, db.....%	1.25	0.48	0.50	0.28	0.40	0.38
Alkalies in ash.....%	0.06	0.07	0.08	0.04	0.12	0.10
Pulverization (%-3mm)	81.0	84.5	93.4	90.1	91.1	82.0
Hardgrove index	65	66	89	84	89	92
Caking Properties						
Free swelling index	8.5	8	7.5	6.5	6.5	6.5
Gieseler plasticity (ddpm)	27 800	195	11.4	3.8	6.7	1.9
Dilatation (c+d).....%	226	66	30	0	7.0	0
Expansion/contraction %	-15	-	-11.3	-13.5	-11.7	-
Carbonization Results						
Maximum wall pressure, kPa	2.1	3.7	7.2	2.1	5.8	16.1
Coke Properties						
Ash.....%	4.2	8.7	9.3	12.0	11.6	8.6
Volatile matter.....%	0.9	0.8	0.8	0.7	0.8	0.6
Sulphur.....%	1.04	0.37	0.38	0.27	0.36	0.32
ASTM stability	38.1	45.1	55.7	51.0	58.1	57.1
JIS DI^{30}_{15}	-	92.1	-	90.8	94.6	93.2
CSR	37.0	62.1	64.0	61.4	73.9	68.3

a coking time of about 13.5 h to 900°C (gross coking time to 18 h) at coal charge bulk densities of 816 kg/m^3.

Comparison of Tables 2 and 4 indicates that none of the cokes made from single Canadian coals meet all of the specifications for coke properties and demonstrates why coal blending is practised at most major steel mills in the world today.

The Nova Scotian coal produces coke with low strength and CSR properties. This is primarily because of the coal's low rank and excessive caking properties. Chemically the coke has excessive sulphur. However, this coal has excellent properties for blending with higher rank coals containing high inerts. Its low ash and high fluid properties (27 000 ddpm) allows it to be blended with most high-rank (low-volatile) coals having high inerts and low sulphur contents to make good coke. The Sydney Steel Corporation has operated for many years with a blend containing 80% Nova Scotian coal and 20% western Canadian coal.

Generally, cokes made from western Canadian metallurgical coals have ash contents that meet the specifications of foreign steel mills but are slightly higher than those of the central Canadian steel mills in Table 2. Most of the coals make cokes that either meet or almost meet both Canadian and foreign steel mills' criteria for strength. Coal A from the Elk River Valley is high-volatile bituminous and, like the Nova Scotian coal, has too low a rank to make high-strength coke although its CSR of 62 is excellent. Coals of this nature - with low sulphur and alkali contents, having caking properties within the optimum range, and producing high CSR coke - are very desirable components in coking blends. Coal B, another coal produced in the Elk River Valley, is a medium-volatile bituminous coal with a vitrinite reflectance of 1.01. It produces cokes with good cold strength and CSR properties and can be beneficiated to slightly lower ash levels than the other medium-volatile coals in Table 4.

Coals C and D are typical of the range of coking properties of most metallurgical coals from western Canada. They are medium-volatile bituminous in rank with higher vitrinite reflectance than coal B and they can be cleaned economically to about a 9.5% ash content to give cokes with ash contents of about 11-12%. Sulphur, alkalies, and other contaminants are generally low. The coals make cokes with good to excellent cold coke strength. The CSR values also range from very good to excellent. Coking pressures for these coals, like the high-volatile coals, are low and present no danger in coke oven operation.

Coal E, a low-volatile bituminous coal, produces coke with high strength and excellent CSR properties. The coal is readily cleaned, with the coke produced from it having an ash content of near the 8% requirement for Canadian mills. The coking pressure of 16 kPa obtained for this coal is considered low when compared with Carboniferous low-volatile coals of similar rank. CANMET no longer carbonizes Carboniferous low-volatile coals (except in blends) because the wall pressure

determined for one of these coals exceeded 140 kPa, at which point the movable wall was backed away from the coking charge to prevent damage to the test oven.

Coke Quality From Two Component Blends of Western Canadian Coals

Table 5 gives pilot coke oven results showing that coke quality can be improved by blending western Canadian coals in binary blends. Blend 1 is a two-component blend containing 65% high-volatile coal A and 35% low-volatile coal E (Table 4). Blends 2 and 3 are binary blends each containing two medium-volatile component coals from western Canada; blend 2 contains 69% coal B and 31% coal C, while blend 3 contains 55% coal D from Table 4 and 45% of another medium-volatile western Canadian coal not listed in Table 4 but having a vitrinite reflectance of 1.08. Results in Table 5 indicate that these blends more than meet all the coke specifications in Table 2 except perhaps the total ash content. For blend 1, the coke ash content of 8.5% is near the desirable level of 8.0% set by the Canadian steel industry; for blends 2 and 3, the ash levels are 10.3 and 11.5%, somewhat high by this criterion but similar to ash contents of many cokes produced in Pacific Rim steel plants (Table 2). ASTM stability and JIS drum indices are very good for these blends, and CSR values are excellent as is the case for most western Canadian coals. Coking pressures for these blends, at 7 to 9.5 kPa, present no problems for the coke maker.

The results in Tables 4 and 5 show that coke strengths of western Canadian coals and blends are much better than would be expected from their low plasticity and dilatation properties. The Gieseler plasticity, and dilatations of coals B to E and blends 1 and 2, are much lower than the criterion set in Table 3 and cast doubt on the value (or at least the universality) of any model incorporating these measurements to predict coke strength for cokemaking purposes.

Table 5 - Analyses of three binary blends of western Canadian coals and their resultant cokes

BLEND PROPERTIES

	Western Canadian Binary Coal Blends		
Coal Charge Properties	Coal Blend 1	Coal Blend 2	Coal Blend 3
Ratio of components	65:35	69:31	45:55
Reflectances of components(a:b)	0.90:1.62	1.01:1.28	1.08:1.27
Mean reflectance Ro	1.13	1.08	1.17
Volatile matter, db.....%	26.9	25.1	24.5
Ash, db.....%	6.5	8.0	9.2
Sulphur, db.....%	0.39	0.46	0.49
Alkalies in ash.....%	0.09	0.08	0.1
Pulverization (%-3mm)	86.1	92.4	90.3
Ash Analysis (%)			
SiO_2	56.38	57.14	58.9
Al_2O_3	27.2	29.11	27.9
TiO_2	1.45	1.76	1.87
P_2O_5	1.18	1.20	1.24
Fe_2O_3	6.0	3.47	3.61
CaO	2.52	2.24	1.53
MgO	0.68	0.58	0.91
Na_2O	0.49	0.10	0.10
K_2O	0.87	0.71	0.85
Caking Properties			
Free swelling index	6	7	7.5
Gieseler plasticity (ddpm)	16.8	12.0	12.5
Dilatation (c+d) %	13	29	31
Expansion/contraction %	-10.0	-12.6	-8.2
Carbonization Results			
Maximum wall pressure kPa	7.3	9.1	9.5
Coke Properties			
Ash	8.5	10.3	11.5
Volatile matter	0.7	0.8	0.6
Sulphur	0.37	0.35	0.43
ASTM stability	58.4	58.2	57.4
JIS DI^{30}_{15}	93.1	93.0	93.6
CSR	67.0	69.0	65.1
Coke reactivity index (CRI)	24.0	23.3	22.6

Table 6 - Properties of good coking Appalachian coal blends and resultant cokes

	BLEND PROPERTIES Appalachian Binary Coal Blends				
Coal Charge Properties	Coal Blend 1	Coal Blend 2	Coal Blend 3	Coal Blend 4	Coal Blend 5
Ratio of components	72:28	70:30	75:25	93:7	65:35
Reflectances of components(a:b)	0.88:1.65	0.95:1.62	1.13:1.22	1.13:1.42	1.06:1.66
Mean reflectance Ro	1.06	1.22	1.17	1.17	1.26
Volatile matter, db.....%	32.9	28.7	28.2	29.0	26.8
Ash, db.....%	6.2	6.2	6.0	5.3	5.6
Sulphur, db.....%	0.89	0.81	0.72	0.62	0.72
Pulverization (%-3mm)	82.7	83.6	87.5	89.2	
Ash Analyses(%)					
SiO_2	50.55	46.4	42.19	41.93	
Al_2O_3	29.1	28.5	27.54	26.92	
TiO_2	1.47	1.3	1.53	1.50	
P_2O_5	0.18	0.24	0.46	0.38	
Fe_2O_3	.8	11.53	10.92	11.18	
CaO	2.81	2.95	4.74	4.70	
MgO	0.92	1.73	1.89	2.05	
Na_2O	0.61	0.80	0.68	0.81	
K_2O		1.55	2.06	1.72	1.96
Caking Properties					
Free swelling index	7	7.5	7.5		
Gieseler plasticity (ddpm)	570	4380.	11090.	6530.	2650.
Dilatation (c+d)	44	134.	242.	248	122
Expansion/contraction	-9.6	-12.8	-9.1	-9.7	-
Carbonization Results					
Maximum wall pressure kPa	12.5	7.0	6.8	26.8	10.3
Coke Properties					
Ash	9.1	8.0	7.6	7.0	7.3
Volatile matter	0.8	0.7	0.6	0.6	0.8
Sulphur	0.63	0.74	0.64	0.62	0.64
ASG	0.894	0.945	0.897	0.885	0.899
ASTM Stability	58.9	58.1	57.6	57.9	58.3
JIS DI^{30}_{15}	94.9	94.4	94.5	95.1	
CSR	61.6	47.5	6.9	53.6	57.4
CRI	31.0	32.7	30.5	32.5	27.0

Comparison Of Cokes Made From Western Canadian Binary Blends With Those Made From Appalachian Binary Blends

The primary objective of doing the carbonization tests listed in Table 6 was not to compare binary Canadian blends with similar Appalachian blends but to investigate the effects of blending different ranks of coal in two component blends on the coke reactivity and CSR properties of high-stability cokes. Nevertheless, cokes from blends in Tables 5 and 6 can be compared since they were carbonized under similar bulk densities (820 kg/m^3) and heating rates (13-14 h coking times to a centre temperature of 900°C) in CANMET's 460 mm wide coke oven.

Component Appalachian coals were supplied by Canadian steel mills. Blends were composed to produce cokes with ASTM stabilities that just meet Canadian steel company specifications, i.e., 58±1. Results in Tables 5 and 6 showed that the ASTM stability requirement could be met by both the Canadian and Appalachian blends used in this study. High-stability cokes could be made from blends having mean maximum vitrinite reflectances from 1.06-1.26. Wall pressures ranged from 6.8 kPa (very acceptable) to 27 kPa (unacceptable) for the Appalachian blends listed in Table 6, as compared to the 7-9.5 kPa for the Canadian coals.

In fairness to the Appalachian blends, higher cold coke strengths were obtained when larger proportions of the higher ranked component coal were used. For example, Appalachian blends 3 and 4 gave ASTM stability factors of 62.0 and 60.3 when component coal ratios were changed to 60:40 and 89:11, respectively. However, coking wall pressures became even higher for these higher stability coking blends (blend 3 giving a wall pressure of 42 kPa).

Tables 5 and 6 show that good coking Appalachian blends generally have much higher Gieseler plasticity and dilatation properties than western Canadian blends producing equivalent coke strengths. Western Canadian coal blends have lower sulphur contents but higher ash contents.

Pulverization is generally easier for the western Canadian coal, presumably a result of its fissured nature.

Tables 5 and 6 show that the CSR and CRI values of cokes produced from the Canadian coals are superior to those of cokes made under identical conditions from the Appalachian blends. The CSR of Appalachian blends ranged from 48 to 62, while those of the western Canadian coals ranged from 65 to 69. Many researchers have shown that optimum CSR and reactivity is achieved at a coal rank of 1.2-1.4 vitrinite reflectance (24). This would imply that coking blends comprised of component coals near the optimum reflectance range would make superior coke than blends having components with reflectance distributions on either side of the optimum range. The results from this study, however, suggest that the rank of the component coals in a good coking blend is not critical to the reactivity and CSR properties of the coke. For the Appalachian blends, blend 1, which had the greatest difference in the rank of the component coals, gave the highest CSR result.

Analyses of the chemical, petrographic, and textural properties of the coals and cokes in this study suggest that the chemistry of the ash in good coking blends is a more important factor in coke reactivity and CSR than the rank of the components or quantity of the ash. The western Canadian coals have a much lower content of basic compounds (Fe_2O_3, CaO, MgO, Na_2O and K_2O) and higher contents of silica and alumina than the Appalachian coals. These parameters have been shown by CANMET and other investigators to be critical in affecting coke reactivity and CSR (26).

The results show that the Appalachian and western Canadian coal properties complement one another. The Appalachian coals have lower ash contents and higher caking properties; the western Canadian coals have better ash chemistry (lower sulphur and basic components), better CSR properties, and lower caking properties, resulting in lower coking pressures.

Coke Quality From Two Component Blends Of Eastern Canadian With Western Canadian Coals

The Nova Scotian coking coal, which is Carboniferous (Appalachian) in age and high-volatile bituminous A in rank, has chemical and thermal rheological properties that ideally complement the western Canadian bituminous coals. The Nova Scotian coal has high sulphur but low ash levels, while the western Canadian coals have low sulphur and somewhat higher ash contents. The Nova Scotian coal has strong caking properties but makes weak coke, while western Canadian coals make unusually strong coke although having somewhat low Gieseler fluidity and Ruhr dilatation properties.

In 1979, a study was undertaken to determine if a coke suitable for industrial use could be made by blending Nova Scotian coking coal with medium-volatile coking coals from western Canada (27). In this study, Nova Scotian coal was blended into two component blends with each of four western Canadian medium-volatile coals having varying ranks (Ro of 1.06 to 1.38). Figure 2 shows that ash and sulphur levels can be made acceptable by using about 40% western Canadian coal in the blends. Figure 3 shows that ASTM stability also attained acceptable levels for two of the blends (NS-F and NS-G) at blend ratios containing about 40% western Canadian coals. These blends contained the higher ranked western Canadian coals F and G having reflectances of 1.38 and 1.27, respectively. Blends NS-H and NS-I contain the lower rank western Canadian coals H and I (1.06 and 1.10 reflectance), and although coke quality improved upon the addition of 25-40% western Canadian coal, the overall ranks of the blends were insufficient to make high-strength coke. ASTM hardness showed similar trends as ASTM stability. CSR values increased as higher levels of western Canadian coals were incorporated into the blends. Coking pressures remained low, less than 4 kPa for all blends, throughout the entire study.

It can be concluded that high-strength coke with acceptable sulphur and ash levels can be made from blends of eastern Canadian and western Canadian coals provided the overall rank or reflectance of the blends falls within the limits defined in Table 3 (Ro of 1.10-1.25). This requires that the higher ranked medium- or low-volatile western Canadian coals be used if only binary blends are desired. The Sydney Steel Corporation has for many years made a low-ash, high-strength coke from a binary blend of Nova Scotian coal and 20-25% low-volatile coal from western Canada.

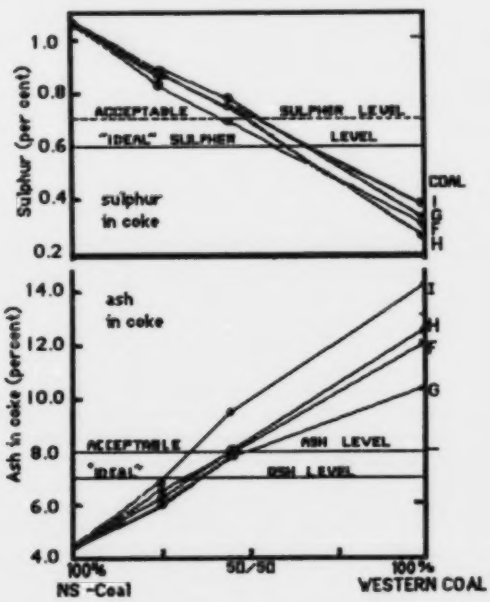

Fig. 2 - Relationship between sulphur and ash in coke and eastern/western Canadian coal composition

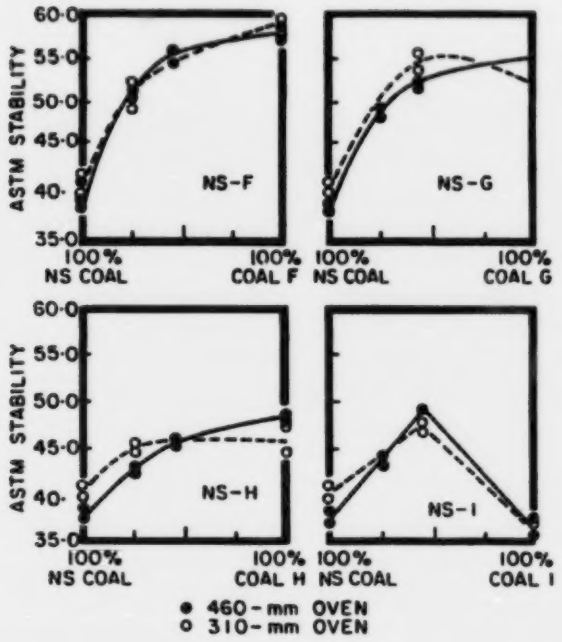

Fig. 3 - Relationship between stability factor and blend composition

Cokemaking With Appalachian Blends Containing Western Canadian Coal

Canadian steel producers produce blast furnace coke from binary blends of one or more low-volatile and high-volatile Appalachian coals. In the selection of binary blends it is important that the softening temperatures and melting ranges of the coals overlap each other to ensure adequate interaction of the components during carbonization. High-volatile coals melt and have fluid ranges at lower temperatures than low-volatile coals. Coke quality can often be improved by adding a medium-volatile (ternary) coal to bridge the fluid temperature ranges.

A CCRA/CANMET investigation was undertaken to determine the effects of incorporating medium-volatile western Canadian coal into high/low-volatile Appalachian blends when carbonized at fast and slow coking rates. Tests were done in CANMET's 460 mm wide test oven at a dry coal charge bulk density of 832 kg/m^3 and 4% coal moisture. Flue temperatures were set at 1065°C and 1250°C for the slow and fast coking rates. Coking times to a centre charge temperature of 900°C were about 20.4 and 14.7 h, respectively, for the slow and fast coking rates. Properties of the coals used in this study are given in Table 7. The Appalachian hv coal has excessive fluid properties and in binary blends with Appalachian lv coals imparts excessive caking capacity. The western Canadian coal sample used in this study had low caking properties (even for western Canadian metallurgical coal) and with a FSI value of 4 could be termed a weak coking coal.

Four separate blends were composed for this investigation containing hv:mv:lv ratios of: 65:0:35; 51:25:24; 36:50:14; and 18:82:0. The ratios were chosen to give the same mean (maximum) vitrinite reflectance of 1.26 for all blends. A summary of the results from the coking tests is given in Table 8. The excessive caking properties of the binary hv-lv blend can be improved to the optimum range (Table 3) by adding 25-50% of the higher inert mv coal. Coking pressures were reduced by adding the mv coal to the blend and by coking at the slower heating rate. Figure 4 shows that 25-50% of this western Canadian coal can be incorporated into hv/lv blend before any significant deterioration in cold coke strength was observed at either fast or slow coking rates. CSR improved as the content of the mv coal in the blend increased and was significantly better at faster coking rates than at slow coking rates, a result found in several investigations at CANMET. Coke sulphur is reduced but an ash penalty is incurred with increased additions of the mv coal.

Table 7 - Properties of coals used for blending in western Canadian/Appalachian coal investigation

Properties	Appalachian Coals hv Coal Blend	lv Coal Blend	W. Canadian Coal mv Coal
Ro	1.05	1.66	1.31
Ash (db) %	5.7	5.4	9.9
Volatile matter, db.....%	31.8	17.4	20.9
Sulphur, db.....%	0.75	0.67	0.41
Gieseler fluidity (ddpm)	23 100.	10.7	1.8
Fluid range °C	391-488	452-496	450-488
Ruhr dilatation (c+d)	276	56	0
FSI	6	7	4

Table 8 - Coal blend, carbonization, and coke quality results from studies done at two coking rates on tertiary blends (of the same rank) made from Appalachian and western Canadian coals

Blend Properties					
% hv:mv:lv	65:0:35	51:25:24	36:50:14	18:82:0	0:100:0
Ro	1.26	1.26	1.26	1.26	1.31
Gieseler fluidity	2650	610	138	10.1	1.8
Dilatation (c+d)	122	78	58	23.0	0.
Carbonization Results					
Slow Coking Rate-Flue temp-1065°C					
Wall pressure (kPa)	8.3	5.4	3.5	3.1	3.1
ASTM stability	61.3	61.2	60.4	55.0	50.5
Hardness	65.8	66.2	65.0	59.7	54.9
+50 mm coke	76.7	74.7	73.9	69.6	64.0
ASG	0.891	0.918	0.944	0.978	1.00
CSR	56.1	56.8	59.9	59.5	57.8
CRI	29.3	27.6	25.7	24.6	26.6
Carbonization Results					
Fast Coking Rate-Flue temp -1250°C					
Wall pressure kPa	10.3	6.9	3.3	2.1	1.2
ASTM stability	58.3	58.7	57.3	50.3	46.0
Hardness	67.3	67.7	68.0	61.8	57.2
+50 mm coke	55.9	53.2	49.2	47.6	43.7
ASG	0.899	0.916	0.937	0.973	0.996
CSR	57.4	59.0	65.6	69.2	60.8
CRI	27.0	26.3	23.4	19.9	25.5
Coke ash.....%	7.3	8.5	9.7	11.3	12.4
Coke sulphur.....%	0.64	0.56	0.50	0.41	0.37

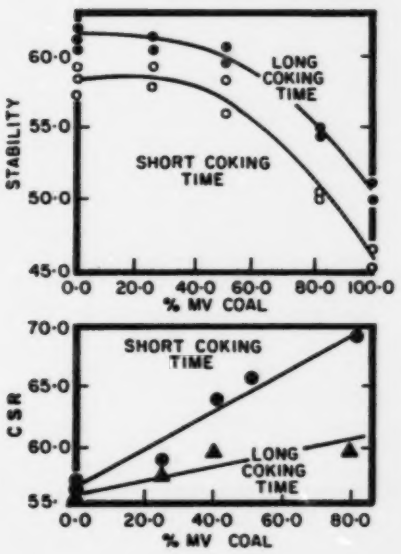

Fig. 4 - The effect of adding mv western Canadian coal to an Appalachian binary blend and carbonizing at two coking rates on the ASTM stability and CSR properties of the cokes

Blending Of Western Canadian Medium-Volatile Coals With Canadian Steel Company Blends

As discussed in the last section, Canadian steel companies primarily use mixtures of several hv and lv Appalachian coals to make up their coking blends, although one company does incorporate some medium-volatile Appalachian coal in their blend. These Appalachian blends generally have optimum or excessive caking properties similar to that shown in the last section. In two separate studies, western Canadian medium-volatile coals were blended into two steel company blends and carbonized in CANMET's 460 mm wide test oven to determine if the quality of industrial coke could be improved by increasing the inert level in the blend. Relatively large amounts of the medium-volatile coals (25-50%) were added to the steel company blend so that differences in coke quality might be readily observed. Properties of the Canadian coals are given in Table 9. Carbonization results of the blends are given in Table 10. Additions of western Canadian medium-volatile coals maintained or improved the coke stability factor, coke hardness, and sulphur contents of the cokes from that of the reference blend. In every test, coking pressures were reduced with the addition of the medium-volatile western Canadian coals. Methods of reducing coking pressures without losing coke strength are of interest to North American coke makers, particularly those operating batteries >5m tall, which are more likely to be

damaged by excessive wall pressures. The Appalachian low-volatile component coals in their blends impart strength to the coke but they also expand during carbonization, creating high coking pressures. Addition of coals A and C to the respective steel company blends improved the coke reactivity and CSR values of the resultant coke. Canadian coal B had little influence on CRI and lowered the CSR value slightly from the original value for the steel company blend. This may be attributable to the difference in the coal bulk densities for these tests. The unusually low CSR values for the cokes made from Steel Company 2 blends are attributable (at least in part) to the lower flue temperatures and bulk densities for these tests. From a coke quality point of view, it would appear that the biggest drawback to using western coal in a Canadian steel company blend is the penalty associated with the increased ash content of the cokes. For the blends studied in this investigation, the coke ash content increased between 0.4 and 2.0% depending on the type and amount of western Canadian coal added. Internationally, the ash levels of the western Canadian coals and cokes do not appear unusually high.

Comparison Of The Benefits Of Adding Western Canadian Versus Appalachian Medium-Volatile Coals To A Canadian Steel Company Blend

In another pilot oven study undertaken jointly with a Canadian steel mill, three medium-volatile coals (one Canadian and two Appalachian), were substituted for component coals in the company's industrial blend. The prime objective was to determine and compare the effects of substituting 15% of the different medium-volatile coals into the blend on coke quality, coking pressure, and per cent contraction (sole heated oven) of the blend. Coal rank and coking results are summarized in Table 11. The Canadian coal and its ternary blends had lower rank (Ro) than the corresponding Appalachian medium-volatile coal blends and consequently produced cokes with slightly poorer cold strength than the Appalachian blends.

Table 9 - Properties of three western Canadian coals substituted into central Canadian steel company blends and carbonized in CANMET pilot coke ovens

	Coal A	Coal B	Coal C	Steel Co. 1 Blend	Steel Co. 2 Blend
Ash, db.....%	9.3	10.0	8.9	6.0	6.4
Volatile matter, db.....%	25.0	21.1	22.6	30.2	30.6
Sulphur, db.....%	0.55	0.27	0.30	0.92	0.75
Ro	1.10	1.38	1.25	1.06	1.16
Gieseler fluidity, ddpm	25.2	46	67.5	281	917
Dilatation (c+d)	37	25	16	- -	91
FSI	7.5	7	7	7	8

Table 10 - Charge conditions, carbonization results, and coke quality drived from two steel company reference coking blends and blends containing western Canadian medium-volatile coals

	Blend Ratios				
	Steel Co. 1 ref. blend (100%)	Steel Co. 1 ref. blend +50% coal A	Steel Co. 1 ref blend +50% coal B	Steel Co. 2 ref blend (100%)	Steel Co. 2 ref blend +25% coal C
Charge Conditions					
Moisture in charge .....%	3.1	3.1	3.1	5.2	4.5
Minus 3.35 mm.....%	88.0	89.4	86.5	88.1	89.0
Coal bulk density (db) kg/m^3	854.	853	821	757	782
Flue temp. control °C	1200	1200	1200	1125	1125
Carbonization Results					
Wall pressure (kPa)	8.3	4.69	5.5	4.5	2.3
Coke yield.....%	72.8	73.8	75.2	72.4	73.7
ASTM stability	61.8	61.9	62.4	57.4	57.1
Hardness	70.8	68.4	71.2	64.8	65.0
+50 mm coke	58.2	54.3	58.3	70.0	71.1
-13 mm coke	3.3	3.4	3.6	2.7	3.0
ASG	0.869	0.934	0.979	0.817	0.881
CSR	54.0	56.2	52.6	39.0	47.1
CRI	34.8	29.2	34.7	38.8	35.3
Coke Ash %	8.1	10.1	10.0	8.7	9.1
Coke sulphur %	0.71	0.64	0.62	0.77	0.63

Table 11 - Comparison of the effect of substituting Western Canadian and Appalachian coals for components in an industrial coking blend

Coals	Ro	Dilatation	Reference Blend	Blend Ratios 1	2	3
U.S. lvb	1.61	75	35	28	28	28
U.S. hvb	0.95	150	65	57	57	57
U.S. mvb - 1	1.39	77	-	15	-	-
U.S. mvb - 2	1.29	131	-	-	15	-
Cdn. mvb - 1	1.14	11	-	-	-	15
Blend Ro			1.15	1.22	1.15	1.05
Dilatation %			31	34	38	21
Expansion/Contraction %			-4.8	-5.1	-5.5	-10.5
ASTM stability			57.2	62.3	58.9	55.7
CSR			61.0	60.0	60.9	67.0

However, the ternary blends containing the Canadian coal had much superior strength after reaction (CSR). The blends containing the Canadian coal had lower wall pressures and better contraction in the sole heated oven than the Appalachian blends, probably because of the combined effect of higher inert contents and lower Ro of the blend.

The Effect Of Mineral Matter Content On The Properties Of Cokes Made From Western Canadian Coals And Blends

Mineral matter (ash) contents of most production coals from western Canada are currently higher than those of coals traditionally used by Canadian steel mills. This programme was carried out to obtain data on how reductions of mineral matter affect the thermal rheological properties of the coal, its petrographic analysis, carbonization behaviour, and the quality of coke produced from the coal and/or blends containing the coal. The results, described in detail elsewhere, should be of use in the cleaning of coals, selecting coal ash contents for resource evaluation, and predicting coke quality from rheological properties (28). The economic aspects of cleaning the coal to the ash levels described were not considered.

Four coals - A, B, C, and D in Table 12 - were each cleaned to different ash contents in a pilot plant to simulate industrial beneficiation by using heavy media cyclones for the +19 mm coal, water only cyclones for the -0.6 mm coal, and froth flotation circuits for the -0.2 mm material. Analyses of the washed coal products are given in Table 12. Coals A and B have a ASTM rank of medium-volatile bituminous, Coal C is high-volatile bituminous, and Coal D is low-volatile bituminous. Mean maximum reflectance, Ro, varies from 0.91 for the high-volatile Coal C to 1.36% for the low-volatile Coal D. The average fixed carbon content of the Coal D samples is 78.4% (dmmf), which is close to the dividing point between low-volatile and medium-volatile, 78%.

Results showed that as ash content decreased, Gieseler fluidities, total dilatations, and melting ranges increased for all coals, while the reactive components in blends A and D increased moderately.

Cokes were made using the three washed products from each coal in the Carbolite and the 310 mm test ovens. Also, the different ash products for the two medium- and low-volatile coals (A, B, and D) were blended with Nova Scotian high-volatile coal and an Appalachian low-volatile coal from the United States (coals E and F, respectively, in Table 13) and carbonized in the 310 mm oven. Blends contained 37.5% E, 12.5% F, and 50% of either coal A, B, or D. Coal C, the high-volatile coal, was blended with 25% low-volatile coal F.

Table 12 - Properties (dry basis) of four western Canadian coals cleaned to three ash levels

	Coal A			Coal B			Coal C			Coal D		
Ash, db ..... %	8.2	7.1	5.3	7.9	5.7	3.1	9.6	6.6	5.1	11.2	8.9	6.8
Volatile matter..... %	24.8	25.1	25.8	22.9	23.5	23.8	30.6	32.2	30.2	19.6	20.4	21.2
Ro ..... %	1.2	1.2	1.2	1.31	1.32	1.32	0.91	0.91	0.94	1.36	1.36	1.36
Reactives ..... %	65.4	69.9	71.5	70.5	72.4	73.3	77.2	81.2	80.0	65.5	71.0	75.1
Ultimate Analysis(%)												
Carbon	81.0	81.9	83.6	83.8	85.1	87.8	77.6	80.2	81.3	80.7	82.4	84.1
Hydrogen	4.8	4.9	4.9	4.4	4.6	4.7	4.9	5.2	5.2	4.4	4.6	4.8
Sulphur	0.24	0.25	0.24	0.72	0.59	0.51	0.71	0.74	0.69	0.39	0.37	0.37
Nitrogen	0.9	0.9	0.9	1.3	1.3	1.3	1.3	1.5	1.5	1.3	1.2	1.3
Ash Analysis(%)												
SiO_2	49.2	51.8	50.0	56.6	51.3	54.6	59.2	57.7	58.3	56.5	55.7	55.7
Al_2O_3	26.7	29.3	29.6	18.6	18.2	19.0	24.4	25.7	26.7	25.5	26.6	28.1
Fe_2O_3	14.4	6.7	7.7	8.8	10.4	9.3	6.0	5.2	4.8	4.8	4.1	3.8
TiO_2	1.4	1.5	1.4	0.7	0.7	0.9	1.2	1.3	1.3	1.1	1.0	1.3
P_2O_5	0.8	0.9	0.9	0.3	0.5	0.7	0.9	1.3	1.3	0.5	0.6	0.7
CaO	1.2	1.4	1.4	3.3	4.6	7.1	1.7	1.6	1.5	2.9	2.8	2.5
MgO	0.6	0.8	0.5	1.8	2.0	2.4	1.0	0.9	0.9	0.8	0.8	0.5
SO_3	0.9	1.1	1.1	3.2	5.6	8.5	0.8	0.5	0.5	3.0	3.0	1.7
Na_2O	1.7	2.0	2.2	0.6	0.9	1.7	0.1	0.1	0.1	1.7	1.8	1.8
K_2O	0.6	0.6	0.7	2.6	1.8	0.6	2.6	2.2	2.1	0.6	0.5	0.5
Caking Properties												
Gieseler Fl (ddpm)	2.6	2.5	4.8	72.	101.	120.	495.	655.	645.	7.5	19.	58.
Dilatation (c+d) %	0.	0.	2.	11.	34.	37.	79.	83.	88.	0.	18.	46.

Table 13 - Properties of cokes made from coals and Appalachian blends containing western Canadian coal at different ash levels

	100% A			50% A 37.5% E 12.5% F		
Ash in Coal A.....%	8.2	7.1	5.3	8.2	5.3	
Stability factor	50.6	50.7	56.2	56.9	58.5	
Hardness factor	63.0	61.1	68.9	68.7	69.7	
Mean coke size, mm	49.5	48.8	45.7	50.8	49.0	
Coking pressure, kPa	4.3	3.6	5.6	4.0	6.5	

	100% B			50% A 37.5% E 12.5% F		
Ash in Coal B .....%	7.9	5.7	3.1	7.9	5.7	3.1
Stability factor	50.6	54.9	61.3	55.3	57.0	59.0
Hardness factor	71.1	71.5	72.3	69.3	68.0	68.5
Mean coke size, mm	54.4	49.5	45.7	51.1	50.8	50.3
Coking pressure, kPa	13.8	21.0	27.6	22.6	14.1	19.2

	100% C			75% C 25% F		
Ash in Coal C .....%	9.6	6.6	5.1	9.6	6.6	5.1
Stability factor	43.1	48.7	46.7	55.4	57.8	57.8
Hardness factor	63.2	66.6	66.3	68.3	69.7	68.5
Mean coke size, mm	50.8	47.2	46.2	52.8	51.3	51.6
Coking pressure, kPa	4.9	6.4	5.9	10.5	14.9	13.4

	100% D			50% D 37.5% E 12.5% F		
Ash in Coal D.....%	11.2	8.9	6.8	11.2	8.9	6.8
Stability factor	53.1	59.0	62.5	58.7	61.8	61.0
Hardness factor	67.6	69.4	72.9	69.5	69.5	71.1
Mean coke size, mm	61.0	55.9	52.1	54.9	53.3	51.3
Coking pressure, kPa	3.4	4.3	25.5	8.4	7.4	19.2

Results from the coking tests in the 310 mm oven are summarized in Table 13. The flue temperature in this oven is programmed to start at 900°C and increase at 19°C/h to 1070°C. The coal bulk density is 817 kg/m^3 and gross coking time is 9 h. The strength of coke made in this oven improved as ash was removed from the four coals. For coals A, B, C, and D, the difference in the stability factors between the high- and low-ash products is 5.6, 10.7, 3.6, and 9.4 units, respectively. Coke strength after reaction and CRI also improved as the ash was removed from the coals, as shown in Figure 5. For the cokes tested, each 1% decrease in the ash of the parent coal improved the CSR factor by about 3.5-5%. For coals A and D, the differences in the ASTM stabilities (and perhaps CSR) of the coke caused by washing the coal can be attributed to changes in both inorganic and organic inert contents of the products. The relatively large improvement in coke strength for low-ash Coal B is a result of the removal of coarse mineral matter during the washing process as well as the reduction of inorganic inerts.

For the cokes made from the blends of eastern Canadian/Appalachian coals and the washed western Canadian coals, coke stability was higher for the

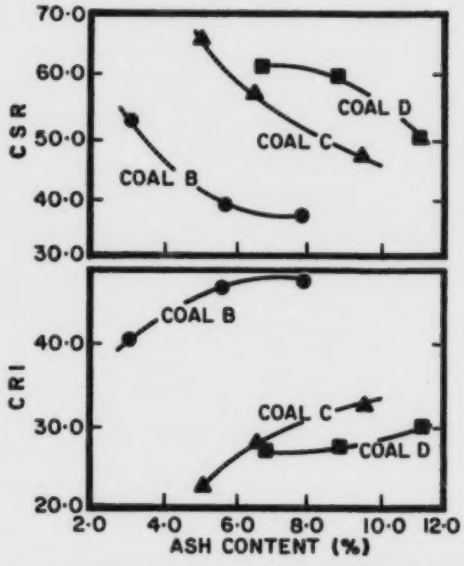

Fig. 5 - Ash content of western Canadian coals versus CRI and CSR of their cokes

blends containing the least ash, but the differences are relatively small. ASTM stability for cokes made from the low-ash blends containing coals A, B, C, and D (described above) are 1.6%, 3.7%, 2.4%, and 2.3% higher, respectively, than for similar high-ash blends.

Coals B and D, the two higher ranked western Canadian coals in this study, gave high coke oven wall pressures during carbonization at the lower ash contents. Coal B, an exploration sample, has high caking properties when compared with western Canadian production coals of this rank, which probably contributed to the high coking pressures. Coal D gave high coking pressures only at the lowest ash content, which can be attributed to the increased petrographic reactives' content for this product. The low-ash products of Coals B and D when blended with the Nova Scotian and Appalachian coals also gave high coking pressures. Although western Canadian coking coals generally have low coking pressures, each coal must be evaluated on its own merits (and potential in specific coal blends) with respect to coking pressures as well as coke quality.

Results from this study would indicate that coke strength and CSR properties improve significantly by beneficiating western Canadian coals to low ash levels but improvements are diminished when the coals are blended with other coals. Some high coking pressures were encountered with the higher rank coals when beneficiated to low ash levels. Unfortunately, current beneficiation technology and market prices make beneficiation of western Canadian coals to very low ash levels uneconomical.

INDUSTRIAL EXPERIENCE WITH CANADIAN COALS

In 1985 Canada exported about 22 million tonnes of "hard" and "weak" coking coals, mainly to Pacific Rim countries such as Japan and South Korea. In Canada, however, Canadian steel mills have been reluctant to incorporate Canadian coals into their blends because of the high transportation cost and the accessibility of Appalachian coking coals from the United States. The Sydney Steel Corporation is the only Canadian steel mill to use exclusively Canadian coal in its coking blend. Their blend is made up of 75-80% Nova Scotian hv coal and a low-volatile coal from western Canada, and makes high-quality coke with ASTM stabilities >58.

The central Canadian steel mills, STELCO Inc., DOFASCO Inc., and Algoma Steel Corp., have used almost exclusively Appalachian coals in their coking blends, either purchased coals or those from captive mines in the United States. In the 1970's, STELCO and DOFASCO both used Nova Scotian hvAb coal in their blends and ran investigations on the possibility of also using western Canadian coals (29,30). At that time both companies concluded that western Canadian lv coals could be substituted for Appalachian lv coals, but the western Canadian mv coals could only replace mv or hv Appalachian coals if ASTM stability were to be maintained. Little concern was paid to coke strength after reaction and reactivity of the coke products. STELCO found some concerns with the fineness, higher moisture, and higher ash content of these coals but concluded that the major drawback to using them was their high cost of transportation.

Recently, Algoma Steel Corporation carried out investigations to determine if a western Canadian mv coal could be successively incorporated into their binary hv/lv blend as found in the CANMET pilot oven investigations (31).

Table 14 shows the coking results from a two-day trial in a 4 m battery, comparing a binary blend with a ternary blend containing 20% western Canadian coal. The Canadian coal was substituted primarily at the expense of the expanding lv coal and as a result had the effect of lowering the blend reflectance and the gas coking pressures.

Table 14 - Industrial trials - Comparison of production blend vs blend with western Canadian mv coal

Coals		% of Production Blend	% of Trial Blend
U.S. hv - 1		65.	60.
U.S. lv - 1		35.	20.
W.C. mv - 1		-	20.
Blend Properties		**Production Blend**	**Trial Blend**
Blend Ro		1.11	1.05
Dilatation	%	33.	35.
ASTM stability		64.7	61.4
+ 50 mm coke	%	50.0	48.1
Gas pressure	kPa	11.7	7.0
CSR		55.3	66.9

Table 15 - Comparison of coke quality with production and trial blends, 1985

Coals Used	Production Blend(%)		Trial Blend (%)	
U.S. lv - 1	22.		28.	
U.S. lv - 2	13.		--	
U.S. hv - 1	43.		40.	
U.S. hv - 2	22.		17.	
W.C. mv - 1	--		15.	
Trial Period	May 13 - June 11		June 12 - Aug. 4	
Coke Properties	Average	Std. Dev.	Average	Std. Dev.
CSR*	62.5	±0.97	62.3	±1.43
Coke size (% +50 mm)	37.0	±6.01	39.1	±6.03
Coke yield	69.4	±1.14	69.0	±1.06
Coke ash	7.6	±0.34	7.6	±0.30
Coke sulphur	0.66	±0.02	0.59	±0.03

*CSR was tested on a composite coke sample during the trial period.

ASTM stability decreased slightly for the blend containing western Canadian mv coal, substantiating the conclusion of the STELCO and DOFASCO researchers that western Canadian mv coals could not be used to replace the lv coals in their blends. However, the CSR of the coke improved considerably by incorporating the western Canadian coal into the blend. This result, along with the reduced coking pressure and only slight decrease in coke stability, encouraged Algoma to conduct longer industrial trials on all operating batteries (two 4 m and two 5 m) using a blend shown in Table 15 that contained 15% western Canadian coal. In these trials, however, the Canadian coal replaced equal amounts of hv and lv coal in the original blend so that the overall rank of the blend did not change (i.e., Canadian coal replaced 8% of the hv coals and 7% of the lv coals). As a result, ASTM stability was maintained at an excellent value of about 62.5. The table shows that CSR improved about 4 units for the blend containing the Canadian coal.

Algoma concluded from the trial that:
- there were no handling or blending problems with this western Canadian coal;
- there were no operating problems with the charging or pushing of coke ovens;
- the resultant coke quality was very similar to the base blend;
- western Canadian coals are compatible and complementary to the world's other coals;
- western Canadian coals, singly or in combinations with other coals, produce coke with low reactivity and highest CSR values (31).

Based on the trial, Algoma used this blend (with 15% western Canadian medium-velocity coal) for about six months of production during 1986.

NON-CONVENTIONAL COKEMAKING

Canada has pioneered the use of many non-conventional methods of cokemaking, usually to produce a special carbon for a specific market. The Curran Knowles ovens at Michel, B. C. were particularly adapted for the coals in use by the Crowsnest Pass Coal Co. at that time to produce a tar high in creosote for the local lumber industry while coke, produced under free expanding condition, had properties suitable for the non-ferrous industry. Other coking or charring units built in Canada included: the rotary hearth carbonizer-Lethbridge Collieries; Lurgi Carbonizer-Bienfait; travelling grate to produce chemical coke from Nova Scotia coal for Shawinigin Chemicals Ltd.; and a shaft furnace, Canmore Mines Ltd., to produce a formed coke from semianthracite/low-volatile coal and tar for the phosphorus industry, but with the potential of producing a blast furnace coke. In the 1960's, CANMET (then the Mines Branch) also initiated investigations on high-density charging of coke ovens using extrusions, pelletizing, and briquetting of coal. In more recent years, CANMET has expanded its effort on non-conventional cokemaking to include topics of preheating, and the addition of caking additives. The summary in this report describes only the studies relating to the potentials of using Canadian coals in these technologies.

THE USE OF ADDITIVES TO CANADIAN COAL FOR IMPROVED COKEMAKING

The addition of refined petroleum pitches, coal tar pitches, and solvent refined coals to coke oven blends is being utilized commercially in Japan and has been the subject of considerable research throughout the world in recent years (32,33,34,35). Additives such as pitch and tar can be added to high inert low caking coals to improve the reactives' content and caking properties of these coals during carbonization.

Western Canadian coals that are generally high in inerts and low in caking properties might benefit from the addition of bitumen and pitch materials to bring their caking properties into the optimum coking range. CANMET has investigated the use of pitch materials with industrial steel company blends, with industrial coking blends containing western Canadian good coking coals, and with single non-coking (at present non-commercial coals) from western Canada. Studies were carried out in CANMET's 460 mm wide oven. Coal was prepared in the conventional manner by pulverizing to approximately 80% -3mm, then pitches with high softening temperatures were blended into the coal as a solid, while those with low softening temperatures were mixed into the coal at 100°C using a kneader.

Investigations into the advantages of adding several pitch materials at the 5% level to a typical steel company blend and to the blend containing 25% high inert medium-volatile western Canadian coal indicated that small improvements over conventional coke were found for coke reactivity when certain pitches were added. However, no significant improvements to ASTM stability (about 57 for both blends) were found with the addition of pitches. Petrographic analysis of the blends indicated that even with the addition of high inert western Canadian coal, the blend had excessive caking properties and, consequently, coke strength could not be expected to improve by the addition of pitch. The study did show that different pitches can increase the thermal rheological properties of coals to various degrees (36).

Another investigation showed coke quality improved after pitches were carbonized with a low-fluid (high inert) western Canadian coal (Ro 1.10%) that had been allowed to oxidize to varying degrees. ASTM stability and hardness factors improved the most when pitches were added to the more highly oxidized coal. Coke stability generally increased as the amount of pitch increased but remained below levels considered acceptable for Canadian steel mills. Coke hardness and CSR improved considerably to 72 and 71, respectively (37).

In a more detailed investigation of three ranks (Ro of 1.07, 1.24, 1.42) of poor coking medium-volatile coals from western Canada, 7% of three commercially available pitch materials were added to pilot oven charges of each coal (38). It would appear that the rank of the coal plays a major role in determining the improvement and ultimate strength of the coke with pitch additives, as shown in Figure 6. Additions were most effective for the two higher rank coals producing cokes having physical properties considered acceptable by Canadian steel companies. Microscopic textural analysis of the coke and coke reflectance measurements showed that pitch additives to the lowest ranked coal had very little effect on texture of coke but they had interacted with the higher ranked coals and changed coke textures. Still, the three pitch materials proved useful in improving coke quality for all coals. Much of the improvement is attributable to an enhancement of coke density caused by slumping of the coal in the coke oven. Coal contraction in the sole heated

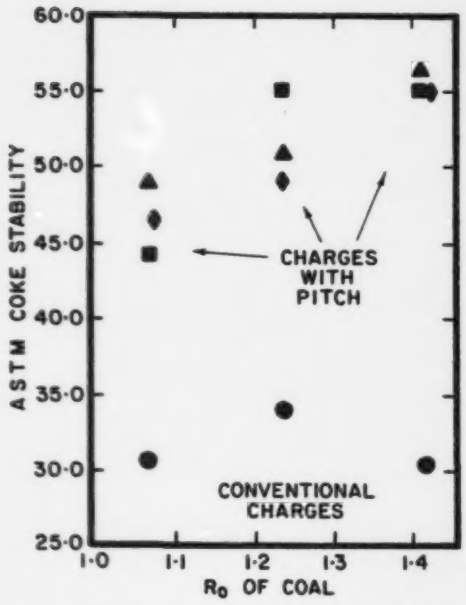

Fig. 6 - Effect of coal rank on the coke stability made from coal/pitch blends

oven increased with the addition of the low melting pitches and correlated with the apparent specific gravity of the cokes made in the movable wall test oven. However, all of the improvements in coke quality cannot be attributed to increased coke density since the improvement in the strength of coke from the coal/pitch blends is greater than the strength associated with increased density of the coke from 100% coal (Fig. 7).

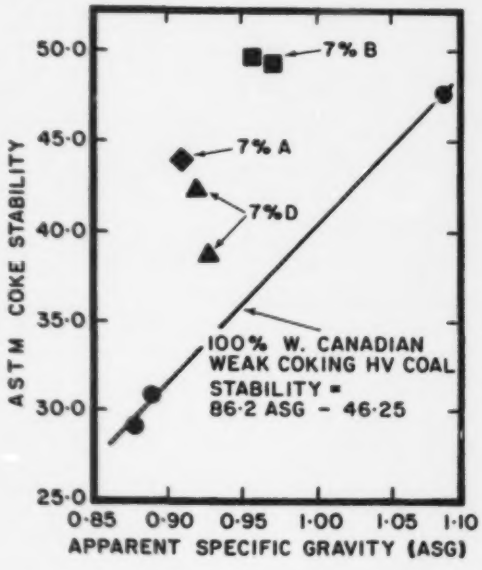

Fig. 7 - ASTM stability plotted against coke apparent specific gravity for coke made from weak coking western Canadian coal (Ro 1.07) with three pitch additives

Generally, the pitch having the best H donor ability, and the highest fixed carbon content, was the most effective in modifying coal rheological properties and the mosaic textures of cokes. Coal-derived pitches (and hydrocracked petroleum) pitches seem to be more effective at improving CSR and CRI than normal petroleum-derived pitches. Other less expensive additives such as decant oil proved to be nearly as effective (39.)

In summary, the low thermal rheological properties of oxidized and weak-coking western Canadian coals from medium-/low-volatile rank are particularly suited for use with good pitch additives or in blends with pitch additives. The pitches interact with these coals during carbonization to form textures that give them increased strength and CSR properties.

Addition Of Chars To Nova Scotian Coking Coal

While the coals in western Canada are inert rich, the coking coal from Nova Scotia has excess caking properties and too low a rank to make good coke. As a result, good coke is usually made by blending this coal with 20-25% high inert low-volatile coking coals. It was anticipated that chars made from the Nova Scotian coal could be blended with the original coal to reduce its volatile content, increase its inert content, reduce its caking properties, and hence improve coke quality.

A study was undertaken to determine if a suitable char could be made to blend with the Nova Scotian hvAb coal to make good coke. Batches of the coal were charred in CANMET's 15 kg carbonization oven at temperatures of 400°C, 450°C, 500°C, and 700°C. Properties of the four chars are given in Table 16. Their volatile matters vary from 6.1 for the high-temperature char to 24.3 for the low-temperature char. The char was crushed to about 80% minus 3 mm in size, then blended with the coal and charged to CANMET's 310 mm wide pilot test oven and carbonized under standard conditions (programmed heating from 900°C to 1070°C at 19°C/h at a charge bulk density of 816 kg/m^3). A coal to char ratio of 70:30 was chosen because dilatations (c+d) were between 50 and 100 for the different char blends.

Results from carbonizations tests are given in Table 17. They show that all the chars with the exception of the 700°C char improved ASTM and JIS drum indices significantly. Coke quality improved

Table 16 - Properties of chars made from Nova Scotian coal at four different temperatures

Proximate analyses (%db)	400° Char	450° Char	500° Char	700° Char
Ash	2.9	3.3	3.3	4.0
Volatile matter	24.3	15.6	11.4	6.1
Fixed carbon	72.8	81.2	85.4	89.9

Table 17 - Carbonization data of cokes made from Nova Scotian coal with four chars

Carbonization Data	Nova Scotia Coal	NS Coal 400° Char	NS Coal 450° Char	NS Coal 500° Char	NS Coal 700° Char
Coal:Char ratio	100:0	70:30	70:30	70:30	70:30
Moisture in charge %	2.9	1.0	1.6	1.6	1.5
Coal bulk density (oven) kg/m^3	819	758	800	784	810
Gross coking time h:min	8:45	10:10	8:50	9:15	9:40
Maximum wall pressure kPa	1.8	1.4	0.5	0.6	1.3
Coke Results					
Coke yield %	60.1	71.7	71.9	73.9	75.9
Mean coke size mm	47.9	49.0	45.5	42.7	91.9
+51 mm coke %	39.2	43.4	32.7	24.9	85.7
-13 mm coke %	4.2	4.0	3.6	3.8	4.9
ASTM stability	36.5	48.4	43.2	43.8	14.8
Hardness	56.5	61.4	57.8	59.6	26.4
JIS DI^{30}	92.0	92.2	91.8	91.5	79.1
JIS DI^{150}	76.4	78.8	77.7	76.6	41.0

for the blends as charring temperature of component chars was reduced. The best coke strength was obtained from the blend containing the char made at 400°C; ASTM stability improved to 48.4 from the 36.5 for coke made from the coal alone. The bulk density of these charges was difficult to control by moisture adjustments and was unusually low for this charge. Consequently, stability results might have been 2-5 units higher at a normal bulk density. The JIS drum indices showed similar trends as ASTM stability with char temperature. The 700°C char acted as an antifissurant and increased the mean coke size from 47.9 mm to 91.9 mm but coke quality deteriorated significantly to a stability of 14.8. Coking pressures were extremely low for all blends.

Although results were encouraging, these additives did not improve coke quality enough to meet the criteria of most blast furnace operators and a higher rank coal is needed in the blend to meet specification. Alternatively, coke quality might be further improved by increasing the bulk density by partially briquetting or preheating these blends.

COKEMAKING WITH PREHEATED CANADIAN COALS

Blends of coals charged to coke ovens usually have moisture contents in the range 5 to 12%. Commercially, preheating of coals is now an established technology that involves drying and heating of a coal or blend to 150-300°C in hot inert gas (fluid bed/entrainment) before transporting it by larry car, Redler conveyor, or pipeline to a coke oven (40,41,42). Advantages to preheating of coal include:

- increased coke strength caused by lower rate of temperature rise in the plastic zone during carbonization, reduced temperature gradient in the semi-coke, and higher coal bulk density;
- increased productivity caused by reduced coking times and higher coal bulk densities;
- wider coal selection since inferior grades of coal can be used to produce strong coke;
- increased refractory life resulting from less thermal shock;
- reduced energy requirement from better thermal efficiency of preheaters than coke ovens;
- reduced coke oven emissions.

In an investigation to determine the benefits of preheating Canadian coals, four coals were studied - three western Canadian mv coals and the Nova Scotian hv coal. Coal properties are listed in Table 18.

In this investigation, coals were carbonized in CANMET's Koppers test oven under several different conditions:

1. Wet charge: coal contained about 6% moisture so the coal bulk density in the oven was low, 664-720 kg/m^3 (dry basis).
2. Air-dry charge: coal was air dried and contained 1.1-2.0% moisture, so coal bulk density was high, 803-912 kg/m^3.
3. Preheated charge: coal was preheated to 180-210°C and coal bulk densities were 803-912 kg/m^3.
4. Preheated to 180-210 and cooled in hopper under nitrogen before charging (Coal A and NS coal only) at two flue temperatures.

Coal was preheated in the charging hopper, which was placed in a gas drying oven controlled at 230°C for periods up to 90 h. The hopper top was covered and sealed with clay and nitrogen was passed into the centre of the hopper at a flowrate of one litre per minute. The nitrogen first flowed through a five gallon can of coal also situated within the oven in order to remove oxygen that might react with the coal.

Table 18 - Properties of coals used in the preheating investigation of CANMET/CCRA

	Western Coals			Nova Scotian Coal
	Coal A	Coal B	Coal C	Coal E
Ash %	9.8	8.4	9.5	4.1
Volatile matter %	21.8	23.5	25.5	33.9
Fixed carbon %	68.4	68.1	65.0	62.0
Gieseler plasticity (ddpm)	20	79	435	27 800.
Total dilatation	39	40	72	226
F.S.I.	7	7.5	5	8.5
Mean Ro max.	1.38	1.27	1.06	0.99

ASTM stability results for the various tests are summarized in Figures 8 and 9. Figure 8 shows that preheating of all coals improved coke strength. Most of the improvement is caused by the higher bulk density of the preheated charges. The ASTM stability of coke from the western Canadian coals is much more sensitive to changes in coal bulk density than the eastern Canadian coal, as shown by the slopes of the lines for the wet and air-dried charges. The ASTM stability improves about 1 stability point for every 14 -16 kg/m^3 increase in bulk density for the western Canadian coals and only 0.3 stability points for the same increase in bulk density for the Nova Scotian coal. Figure 8 also shows that the bulk density of air-dry charges was very similar to those of preheated charges. The differences in the coke stability factors between preheated and air-dry charges are therefore attributed solely to preheating and not to bulk density effects. The change caused by the preheating effect is represented by the dashed lines in Figure 8 that show the preheating effect is very beneficial for the Nova Scotian hv coal and blends containing this coal but detrimental for all the western Canadian coals when carbonized alone. When the Nova Scotian coal was preheated to 204°C, the ASTM stability of the resultant coke was 53, a value approaching the acceptable limit in smaller blast furnaces. Preheated blends containing 75% Nova Scotian coal with 25% western Canadian coal A gave an ASTM wharf stability of 57.8, acceptable for most blast furnaces. Coking pressures for this blend remained low (5 kPa) as for all blends tested in this investigation. However, coal selection with respect to coking pressure is critical for preheated charges, because changing coals subject to expansion at high bulk densities could cause severe coke oven damage. The Canadian coals investigated in this study caused no pressure problems.

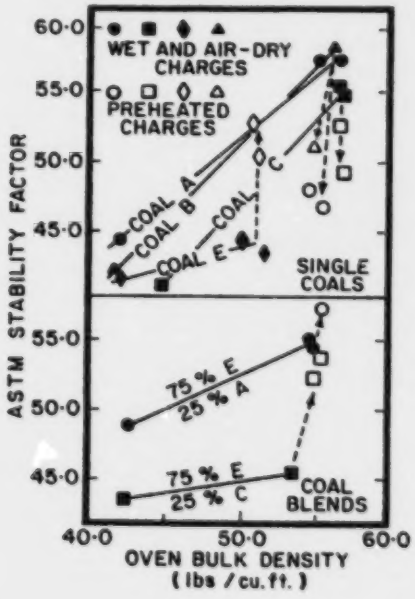

Fig. 8 - Relationship between ASTM stability factor and coal bulk density in the oven for wet, air-dry, and preheated charges

Figure 9 shows the effects of flue temperature on ASTM stability for the air-dried charges of the Nova Scotian coal E and western Canadian coal A (a second set of coal samples were used). ASTM coke stability from western Canadian coal deteriorated for faster coking rates (higher flue temperatures) while it remained unchanged for the Nova Scotian coal. Coke from the preheated, then cooled, Nova Scotian coal had the same stability as the air-dry charge, precluding the possibility that significant oxidation during preheating improved coke quality by decreasing the coal's reactives/inerts ratio; a theory put forward by some researchers (43). However, the results for the western Canadian coal show that ASTM stability for a preheated, then cooled, charge remains at the same level as the preheated charge and 3-5 points lower than the air-dried charge, which suggests that some coal deterioration, perhaps oxidation, has occurred during the preheating process.

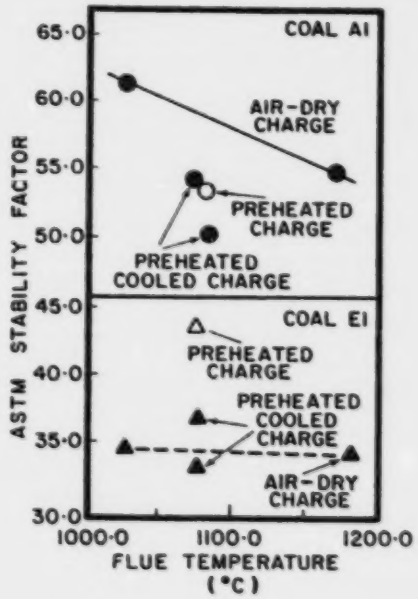

Fig. 9 - Relationship between the ASTM stability factor and the oven flue temperature for preheated, preheated and cooled, and air-dry charges

Figure 10 shows several relationships between caking (and/or coal rank) properties of the coals investigated and the improvement to coke stability by preheating charges compared to air-drying the charges. Apparently, the highly fluid coals of

lower rank such as the Nova Scotia coking coals are the most suitable coals for preheating. If any new coking plants in the Maritimes are to be built, preheating of the charges would appear to be a viable option.

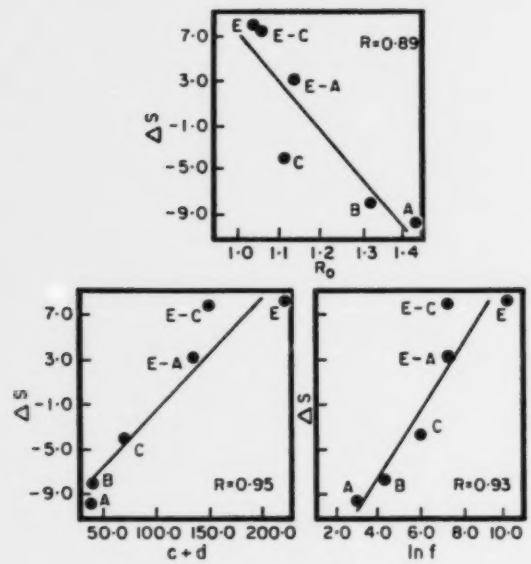

Fig. 10. Relationship between ΔS, the difference in the ASTM stability factor between preheated and air-dry charges and (a) the mean maximum reflectance, Ro, (b) total Ruhr dilatation C+d, and (c) the natural logarithm of maximum Gieseler fluidity (in f)

PARTIALLY BRIQUETTING CANADIAN COKING COALS AND BLENDS CHARGED TO COKE OVENS

Over the last ten years, partial briquetting of coke oven charges has become an alternative to conventional cokemaking at many Japanese steel mills. Partial briquetting of charges is one of several methods to improve coke quality by increasing the coal bulk density in coke ovens. Other methods include oiling, preheating, drying, and mechanical densifying of the coal charge. Partial briquetting involves briquetting a coal or coal blend and uniformly mixing the briquets with a loose coal blend before dropping into the coke ovens. Microscopic examination of cokes has attributed improved coke strength to the formation of a denser coke, which has contracted less and has a better continuity of cell walls than conventional coke made from the same coal. Alternatively, partial briquetting can be used to maintain coke quality while using significant amounts of cheaper, poorer quality coals or non-coking materials.

CANMET has carried out several pilot-scale investigations of the partial briquetting of coke oven charges. The tests have been done in a 460 mm wide oven at two heating rates. Briquets generally made up 30% of the coal charges to the oven and were held together by 6% binder. The loose coal charged usually contained 6% moisture. Figure 11 shows a flow diagram of the procedure used. The majority of these investigations have utilized Appalachian-type coals readily accessible to the Canadian steel producers in central Canada. The studies have shown that coke made from coal blends used by Canada's four major steel producers can be improved by 2 to 6 ASTM stability units above that of conventional charging by partially briquetting 30% of the coal charged to the coke oven (44). One of these blends, used by the Sydney Steel Corporation, was an all-Canadian blend containing Nova Scotian high-volatile coal and a western Canadian low-volatile coal. Another investigation showed coke oven productivity can be increased about 20% by carbonizing a partially briquetted industrial blend at faster heating rates, before coke quality deteriorates below that of the conventional charge (45). Considerable amounts of poor and non-coking materials can be added to the briquetted portion of partially briquetted industrial-type charges before coke quality deteriorates below that from conventional charges (46).

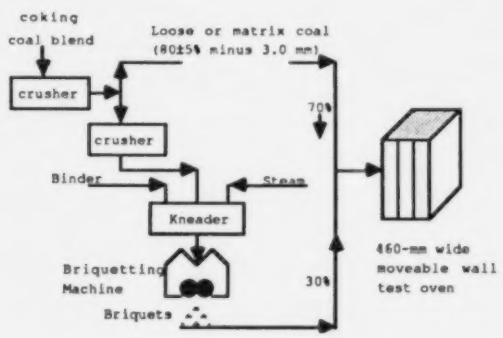

Fig. 11 - Flow diagram of CANMET's partial briquetting procedure

Partial briquetting with single production quality Canadian metallurgical coals has shown that western Canadian coals are suited to partial briquetting technology. Nova Scotian metallurgical coal, like most hvA bituminous coals of Appalachian age, gave no improvement to conventional coke quality when carbonized in a charge containing 30% briquets (46). A hvA coal from western Canada (similar to Coal A in Table 4) did show a small improvement in coke strength (about 1.7 stability units and 1.9 JIS DI^{30} units) when carbonized 30% partially briquetted. Table 19 compares the test results of conventional and 30% partially briquetted coke oven charges carbonized

Table 19 - Carbonization and coke results from conventional and 30% partially briquetted charges of western Canadian low- and medium-volatile coals.

		lv coal		mv coal	
Coal Charge Properties		Conv. Charge	Partial Briq.	Conv. Charge	Partial Briq.
Mean reflectance Ro		1.59	1.59	1.34	1.34
Volatile matter (db)		17.8	17.8	19.3	19.3
Ash	(db)	7.4	7.4	10.2	10.2
Sulphur		0.40	0.40	0.25	0.25
Pulverization (%-3mm)		89.9	89.9	91.6	91.6
Moisture		6.1	4.6	6.0	4.6
Free swelling index		7		5.5	
Gieseler plasticity(ddpm)		1.3		3.5	
Dilatation (c+d)		0		29	
Carbonization Conditions and Results					
Flue temperature Control	°C	1225	1225	1225	1225
Calc charge dry bulk density	kg/m^3	715	794	728	814
Maximum wall pressure	kPa	4.42	6.2	1.2	3.6
Coke Properties					
+51 mm coke	%	44.7	46.8	47.3	38.3
-13 mm coke		21.8	4.9	4.9	3.9
ASG		0.860	0.89	10.95	0.989
ASTM stability		46.2	57.5	53.4	60.9
ASTM hardness		53.8	65.9	72.0	72.3
JIS DI^{30}/15		86.0	94.2	91.8	94.4
JIS DI^{150}/15		69.1	84.0	79.1	84.8
CSR		-	-	49	67

at a flue temperature of 1225°C for two (low-volatile and medium-volatile) western Canadian coals. Other tests done at slower coking rates using a flue temperature of 1125°C are not included but show similar trends (47). With the exception of FSI, both coals had rather low thermal rheological properties not untypical of western Canadian coking coals of this rank. Carbonization of the medium-volatile coal 30% partially briquetted produced cokes of superior quality compared to that from the same coal conventionally charged. Coke strength after reaction and coke reactivity improved about 18 units, from about 49 for the conventional coke to 67 for the partially briquetted coke. ASTM stability and the JIS drum indices also improved significantly by partial briquetting. Coke oven wall pressures increased to 3.6 kPa upon partial briquetting of the charge but remained at a level considered safe by cokemakers.

Coke quality for the partially briquetted low-volatile coal improved even more than the medium-volatile coal when compared to conventional charges; ASTM stability improved by 11-13 units while the JIS drum indices improved by about 3-5 units. Compared to conventional charges, the amount of coke breeze from partially briquetted charges was markedly improved. Figure 12 illustrates ASTM stability factors plotted as a function of bulk density and includes results obtained at different flue temperatures. The points on the figure show that changes in flue temperature had little effect on the ASTM stability factor for conventional charges; ASTM stability appeared to decrease slightly for partially briquetted charges at increased flue temperature. Similar tests on industrial Appalachian blends showed significant deterioration to cold coke strength by increased coking rates. Figure 12 shows two relationships. The upper line represents the improvement in stability caused by increased coal bulk density from partially briquetting this lv coal. The lower line represents only conventional charges and shows the improvement in ASTM stability caused by ad-

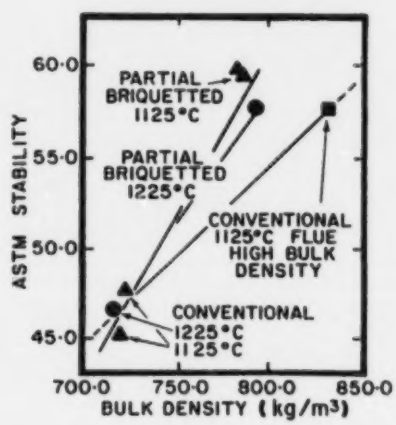

Fig. 12 - Effect of changes in the coal bulk density in the 460 mm test oven on the ASTM stability factor of coke made from western Canadian low-volatile coal by conventional and partially briquetted charges

justment of charge moisture. Thus, the finer pulverization of the coal in the briquettes, the addition of the PDA pitch material, or just the briquetting effect improved coke stability more than would be expected from increased bulk density alone. Relatively large coke oven wall pressures were generated at the higher bulk densities for the low-volatile coal. Although care must be taken to ensure safe wall pressures, the very large improvements to coke quality when carbonizing this coal 30% briquetted suggested it should be an excellent blending coal for partially briquetted charges.

The effectiveness of high-volatile Canadian coals in partially briquetted charges was also investigated at CANMET. Four different hv coals were used with the lv coal to determine which type of hv coal would be most effective for replacing lv coal in partially briquetted blends. The coals were:

1. Appalachian-lv, good coking coal.
2. Appalachian-hv, high fluidity, good coking coal.
3. Appalachian-hv, low fluidity, poor coking coal.
4. Nova Scotian-hv, high fluidity, metallurgical coal.
5. Western Canadian-hv, low fluidity.

The hv coals were each blended with the prime lv coal at hv:lv ratios of 75:25, 88:12, and 95:5, and the resultant blends carbonized conventionally and then 30% partially briquetted.

Coke strength indices of all partially briquetted binary blends were better than those of the corresponding conventional charge (Fig. 13). Partial briquetting improved ASTM coke stability and hardness the most for the binary blends containing the low-fluidity western Canadian coal, and then for the blend containing the highest rank Appalachian hv coal. Smaller improvements were found for the blends containing the Nova Scotian hv coal and the poor coking Appalachian coal. Maximum replacement of lv coal occurred by partial briquetting the blends containing the western Canadian hv coal. Figure 13 shows that partial briquetting a blend containing 91% western Canadian hv and 9% Appalachian lv coal would maintain coke quality at the base level.

Table 20 - Properties of component coals used in binary partially briquetted blends

Properties		Coal 1	Coal 2	Coal 3	Coal 4	Coal 5
Volatile matter	(db)	18.8	32.9	34.4	32.8	32.0
Ash	(db)	7.0	6.0	7.2	3.1	5.4
Ro		1.67	1.05	0.92	1.00	0.94
Pulverization	(%-3 mm)	90.0	85.1	84.8	83.5	84.6
Dilatation	(c+d)	33	111	40	167.	37
Gieseler plasticity	(ddpm)	10.4	1900	327	24 700	339
FSI		7.5	8.0	3.5	8.0	8.0

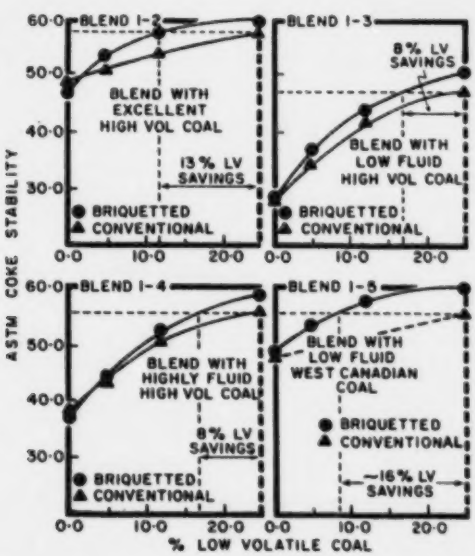

Fig. 13 - Coke stability of binary blends carbonized conventionally and partially briquetted

Partial briquetting of Canadian steel company blends containing western Canadian medium-volatile coals has also been investigated. Coals A and B, as listed in Table 9, were each blended with Steel Co. 1 blend and charged 30% partially briquetted to a 460 mm wide test oven. Results given in Table 21 show that excellent quality coke can be made from any of the blends listed by partially briquetting 30% of the charge. ASTM coke stability had increased from 2-5 units over comparable conventionally charged blends. However, partial briquetting increased the coking pressures to dangerously high levels at the coking temperature and charge bulk density used. At a coal bulk density of 925-932 kg/m^3, the incorporation of western coals A and B decreased coking pressure slightly from 17.4 to 15.1 and to 12.2 kPa, respectively. The charge at the higher coal bulk density (951 kg/m^3) resulted in higher pressures even with the inclusion of 50% western Canadian coal. The carbonization conditions used in this study were more extreme (3% moisture and higher bulk density) than previously used in the partial briquetting studies and may not be representative of industrial oven pressures. Currently, a program is underway to relate industrial oven pressures to test oven pressures.

The incorporation of 50% western Coal A into a partially briquetted blend of steel company coal had little effect on the coke quality parameters since all cokes were excellent. Coke reactivity (CRI), CSR, and coke ASG improved, but the ASTM and JIS tumbler indices decreased slightly from those of the partially briquetted steel company blend. Incorporating coal B into partially briquetted charges generally maintained or improved the ASTM and JIS indices over that of the company blend with partial briquetting.

Canadian non-coking coals and additives have been used in partially briquetted blends of Nova Scotian and Appalachian coals (coals 1 and 4 in Table 20) to determine if coking coals can be replaced with cheaper, poorer coking coals. Researchers at Sumikin Coke Company have indicated that partial briquetting enables replacement of 15 to 20% of the conventional coal charge with non-coking coals while maintaining the original coke strength (48). Small-scale coking tests at CANMET indicated that at least 10% oxidized bituminous coal from western Canada could be added to the briquetted portion of a 30% partially briquetted charge without deteriorating coke quality (49).

Table 21 - Charge conditions, carbonization results and coke quality derived from 30% partially briquetted charges of a steel company reference coking blend, and blends containing western Canadian medium-volatile coals

	Blend Ratios of 30% partially briquetted charges			
	Steel Co. 1 ref. blend (100%)	Steel Co. 1 ref. blend +50% coal A	Steel Co. 1 ref. blend +50% coal B	Steel Co. 1 ** ref. blend +50% coal B
Charge Conditions				
Moisture in charge	2.4	2.6	2.5	2.5
%minus 3.35 mm	91.6	92.6	90.6	93.7
coal bulk density (db) kg/m^3	925	931	951	931
Flue temp. control °C	1200	1200	1200	1200
Carbonization results				
Wall pressure (KPa)	17.4	15.2	23.2	12.2
Time to 900 °C (h:min)	16:37	16:50	17:34	17:05
Coke yield	71.8	74.6	76.0	75.7
ASTM stability	64.2	62.7	67.0	64.2
Hardness	72.5	71.4	74.0	73.0
+50 mm coke	51.9	51.9	53.0	53.0
-13 mm coke	2.8	2.8	3.1	2.8
ASG	0.906	0.955	0.995	0.980
JIS DI^{30}	95.8	93.9	94.9	95.3
JIS DI^{150}	86.0	84.3	86.2	86.0
CSR	60.5	62.8	61.0	57.0
CRI	31.6	27.3	31.7	33.7
Coke ash %	8.1	10.1	10.0	10.0
Coke sulphur %	0.71	0.66	0.65	0.65

** 70% loose coal (71% steel co. blend + 29% Coal B) + 30% briquets (100% coal B)

The blend used as the reference for this pilot-scale investigation contained 75% of Nova Scotian hv coal 4 and 25% of the Appalachian lv coal 1 in Table 20. Tests were conducted to determine the maximum amount of additive or non-coking coal that could be substituted into the coking blend. The additives and non-coking coals were:

1. coke breeze
2. delayed petroleum coke (VM-18.2%, 4.2% sulphur)
3. Canadian hvA bituminous, high-ash, thermal coal, Ro- 0.73, ash 15.7%, G. fluidity-5.3 ddpm
4. Canadian semi-anthracite, VM 12.5, ash 9.5, Ro 2.15.

Figure 14 compares the ASTM coke stabilities from all tests of partially briquetted charges with poor and non-coking materials added to the briquetted portion of the blend. For this study petroleum coke was the best additive, then the poor coking hvA coal from Nova Scotia, the semi-anthracite from western Canada, and finally coke breeze. The figure shows that about 60-65% of the hv thermal coal could be substituted into the briquets before coke strength deteriorated to below that of the non-briquetted good coking blend. The figure also shows that semi-anthracite additions to the briquets did not deteriorate ASTM coke stability until the additions exceeded about 33% of the briquet (10% of blend); and the stability of the partially briquetted charges exceeded that of the conventionally charged base until the briquets contained more than 45% semi-anthracite. Petroleum coke proved to be an excellent additive to the briquetted portion of this base blend, allowing up to about 75% substitution. Generally, all additives decreased coke oven wall pressures. The coke breeze and semi-anthracite behaved as antifissurants and coke size increased.

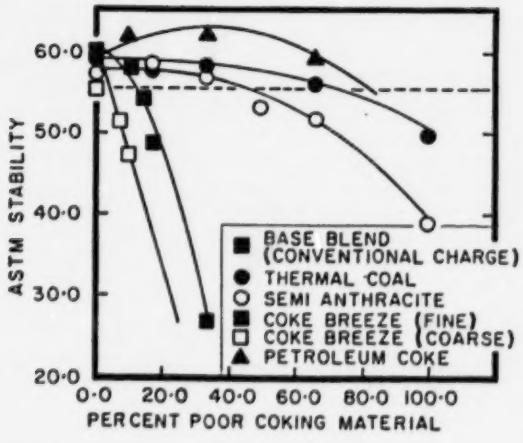

Fig. 14 - Effects of adding various materials to briquets of 30% partially briquetted coke oven charges upon ASTM stability

Commercial blends from four Canadian steel companies were carbonized conventionally and 30% partially briquetted containing a PDA binder and 50% Canadian semi-anthracite to determine if similar levels of non-coking materials could be added to commercial blends (as found for the binary blends). Carbonization results indicated that this amount of non-coking coal could be added into the briquets of 30% partially briquetted blends and that coke quality would be improved or maintained to that of the conventionally charged commercial blends for three of the four steel companies (46). Improvements were related to the fluidities of the commercial blends.

Partial briquetting of Nova Scotian hvA coal containing petroleum coke was also investigated (46). Petroleum coke proved to be an excellent substituent in a good coking coal blend of partially briquetted charges and was further used to determine if it could replace totally the lv coal used in blends with Nova Scotian coal. Delayed petroleum cokes have VM contents (13-18%) similar to lv coals but have high inert contents. Delayed petroleum cokes, when blended with Nova Scotian hv coal, lower the coal's excessive caking properties for cokemaking. Adding 20% petroleum coke to the Nova Scotian coal coked conventionally improved coke stability from 38 for the coal alone to 46.0, which is still substantially lower than the 56.5 stability obtained from the hv-lv blend (Fig. 13). For the petroleum coke/Nova Scotian coal blend, 50% of the charge was partially briquetted in an attempt to achieve acceptable coke strength and because wall pressures for the tests were extremely low. Several partially briquetted charges with different blend compositions were investigated. The best ASTM coke stability at 51.2 occurred for the 50% partially briquetted charge in which the briquets contained 59% coal, 35% petroleum coke, and 6% binder; the matrix blend contained 20% petroleum coke. Cokes of this strength may be sufficient for small blast furnaces but for most operations these results indicate that petroleum coke (like the chars described earlier) can not totally replace low-volatile coal in Nova Scotian coking coal blends even if the charges are partially briquetted. Benefits from including petroleum coke in partially briquetted charges were improved coke yields and improved coke oven productivity, a result of shorter coking time presumably caused by the high thermal conductivity of petroleum coke.

FORMED COKE MADE FROM CANADIAN COALS AND CHARS

Formed coke is a term used to describe agglomerates made from carbonaceous materials such as coal, petroleum coke, etc. Formed coke processes can utilize weakly or non-caking coals in cokemaking and have the potential to:

- reduce capital and operating costs;
- offer greater flexibility of production;
- improve blast furnace performance;
- reduce coke-making pollution (50).

The potential advantages of formed cokes have led to the development of more than twenty processes, of which eight may be considered close to commercial exploitation (51). These processes can be broken into three main groups based on the type of binder used during agglomeration:

- pitch binder
- coal binder
- binderless

although some processes utilize more than one type of binder. Binderless and caking coal binder processes usually have a hot agglomeration step to "soften" the coal, whereas pitch binder processes normally use low-temperature agglomeration.

The Clean Coke, the FMC, and the HBNPC processes are examples of systems using binder in the production of formed coke. These processes generally involve low-temperature carbonization of a coal to produce char and tar, then cold agglomeration (briquetting or balling) of the char using the tar as binder, followed by calcination of the agglomerate to make formed coke. The HBNPC process is more diversified and a variety of coals or coal blends can be used as well as chars.

The BBF-Lurgi process, the Australian Auscoke, and the Luxembourg Ancit processes are typical of hot-briquetting processes that use caking coal as the binder. The processes require approximately 65-70% of inert low-volatile coal (anthracite) or char to be preheated to about 500-700°C and blended with the caking coal, so that the temperature of the blends approaches the optimum fluid temperature of the caking coal. The blend is briquetted at this temperature and the resulting briquets carbonized in a shaft furnace.

CANMET has researched formed coke both in-house and under contract for many years. In the 1950's and 1960's CANMET, in co-operation with Canmore Mines Ltd., developed a pitch binder process in which a blend of semi-anthracite and western Canadian coking coal was briquetted, the briquets being oxidized and heat treated in a vertical shaft furnace. The industrial briquets were very strong and had the potential to be used in blast furnace operations, although the formed coke was actually used in the production of phosphorus. In the 1970's CANMET studies were oriented toward hot-briquetting processes using caking coal as binder, although some investigations on pitch binder and binderless briquetting systems were carried out.

Much of CANMET's formed coke research has been in the optimizing of process variables so that CANMET can simulate existing processes with the objective of evaluating the potential of Canadian and other coals in formed coking processes. Generally, Canadian coals have performed rather well and can be used as one or more of the feed material in various processes. For example, the Nova Scotian hvA coking coal is an excellent binder coal in hot-briquetting systems either with its own char or chars of other coals. Although some western Canadian coals can be used as a binder coal, they are inferior as a binder to the Nova Scotian coals and would be more suited for use in conjunction with a pitch binder in coal/char systems or binderless briquetting/carbonization processes.

In the early 1970's CCRA and CANMET had a variety of North American coals evaluated in the BBF-Lurgi (52) and HBNPC processes (53). Canadian coals investigated included: Devco, Cardinal River, Balmer, Coal Valley, Canmore, and Gregg River. Coal/char systems using Nova Scotian coals were found to make excellent formed coke. BBF rated western Canadian coal/char systems as marginal and recommended that additional pitch binder be used to make suitable briquets (52). Results of final briquet strength plotted in Figure 15 showed that the process is dependent on the maximum dilatation of the binder coal being greater than about 100%. The western Canadian medium-volatile coking coals have unusually low dilatation properties and it is unlikely that they could be used as binder coal in a hot-briquetting process.

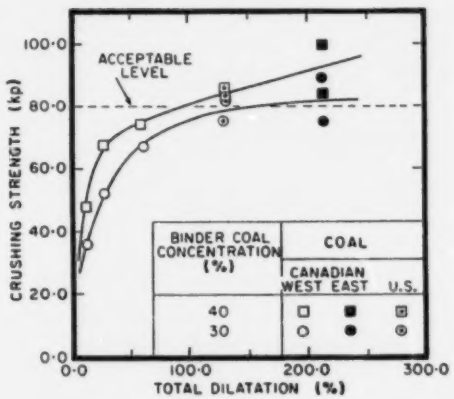

Fig. 15 - Influence of binder coal total dilatation and concentration on hot briquette crushing strengths - plotted from BBF laboratory data

A moderately caking western Canadian hvA coal was compared with Nova Scotian hvAb coal when used as binder coals in a hot-briquetting process with chars made from three Alberta hvC bituminous non-coking coals (54). A char made from an Alberta hvCb coal was blended with caking coal at about 500°C. The blend was briquetted and briquets cured at 550°C in a fluidized sand bed. Results in Table 22 show that the coal/char briquets made using Nova Scotian coal were superior to those made using a western Canadian hv coal as binder, again showing the limitations of western Canadian coal in processes using char as the briquet filler.

The above investigation also showed that the strength of formed coke is dependent on char properties. The properties of char appear to influence briquet densification as well as the wetting of the binder/char interface (55).

Table 22 - Crushing strengths and abradiability indices of hot and heat-treated hot briquets made from various coal/char combinations

Combinations used in hot briquets		Crushing strength of hot and heat-treated hot briquettes kPa		Abradability index for heat-treated hot briquets (%)
Alberta Char	HvAb Coal*	Hot	Heat-treated	
No. 1	(a)W. Cdn	1690	1370	26.7
No. 1	(b)Nova Scotian	3180	7450	13.0
No. 2	(a)W. Cdn	3375	4010	49.5
No. 2	(b)Nova Scotian	3340	7390	-
No. 3	(a)W. Cdn	1443	966	27.0
No. 3	(b)Nova Scotian	6356	5318	34.0

*Experimental conditions:
(a) 45 percent W Cdn coal with char - retained in 515°C fluid bed unit for 1 minute.
(b) 30 percent Nova Scotian coal with char - retained in 470°C fluid bed unit for 5 minutes.
After Leeder and Malette (52).

Pitch-bound briquet tests carried out at HBNPC, using the same coals as in the BBF hot-briquetting study, gave quite different results (53). The process makes briquets with a pitch binder and a blend of coking coal with a larger portion of a lower non-swelling coal. The briquets are then oxidized and heat treated to improve their mechanical and high-temperature properties. The results of the HBNPC laboratory tests appear in Table 23. Generally, briquets made from a fluid coal as indicated by its high FSI (e.g., 6.5) were poor. Coals with low or no FSI tended to yield acceptable oxidized briquets. The eastern Canadian coal that gave the best results as a hot-briquetting binder coal could only be tolerated in very limited portions in the HBNPC blend and probably should not be used at all. Western Canadian coals generally made very good briquets. These conclusions are tentative since the treatment of the briquets included only oxidation and not a final high-temperature treatment.

Table 23 - HBNPC Laboratory formed coke results with Canadian coals

Briquet composition*(%)						Briquet Crushing Strength**	
	Western	Eastern					
Coal	Canadian	Western Canadian Coking Coals			Canadian	Green	Oxidized***
Rank	Semi-anthracite	mvb#1	mvb#2	mvb#3	hvb	(kPa)	(kPa)
FSI	0.	5.5-6	6.5	1.5-2	8-8.5		
	80.	-	-	-	20.	8 000.	16 000.
	85.	-	15.	-	-	13 900.	>25 000.
	80.	20.	-	-	-	10 200.	>25 000.
	-	-	25.	75.	-	7 500.	15 000.
	-	-	35.	65.	-	8 500.	18 500.
	-	-	40.	60.	-	7 000.	25 000.
	-	-	100.	-	-	8 500.	0.
	-	-	50+50. Petroleum Coke	-	-	11 500.	0.
	100.	-	-	-	-	11 000.	25 000.
	50.	-	20.	30.	-	10 500.	21 000.

* 9% coal-tar pitch with a softening point of about 70 °C was used as binder
** Crushing strength between parallel plates on 3 cm diam by 2.5 cm high briquet
*** Anything greater than 12,500 kPa is considered acceptable.

CANMET has also prepared formed coke using binderless briquetting of western Canadian mv coking coals and blends of the coals with oxidized western Canadian mv coal. The oxidized and metallurgical coals were blended as received (80-85% minus 3 mm), 10% water was added, and the blends were briquetted at about 42 000 kPa pressure. The weak briquets were carbonized in a sand-filled carbonizer programmed from ambient temperature to 1000°C at about 3°C/min. For one mvb coal from southeast British Columbia, very strong formed coke was made by blending the coal with 25% oxidized coal from the same region. In a follow-up investigation using another coal from southeast British Columbia that was allowed to oxidize at room temperature, the strength of formed coke made by the above procedure could be improved by finer pulverization of the coal and/or increased oxidation of the coal. Both decreased sizing and oxidation reduced the amount of swelling of the briquets during carbonization and improved their strength, as illustrated in Figure 16. The oxidized western Canadian coal showed no dilatation or FSI properties but had sufficient caking properties under the conditions of briquetted carbonization to give a very strong, dense, and fissure-free formed coke (56). Japan's Nippon Steel Corporation is currently carrying out blast furnace trials using a formed coke containing oxidized metallurgical coals from northeast British Columbia (57).

Both coking and non-coking coals from eastern and western Canada can be used successfully in formed coking processes to produce high-strength coke.

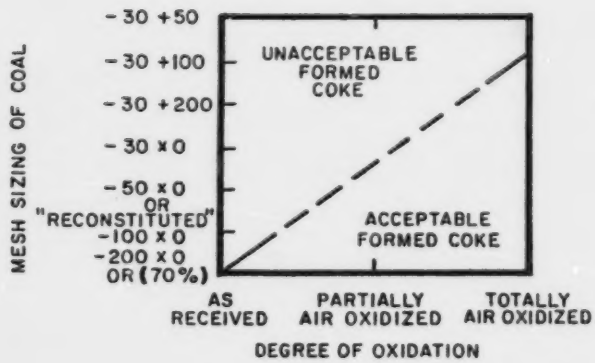

Fig. 16 - The effect of coal size and oxidation on formed coke made from all-coal briquets

LABORATORY PROPERTIES

The preceding discussions have shown that high-quality coke can be made in pilot oven tests and industrially from conventional charges of coals and blends produced in Canada. For several years, Sydney Steel Corporation has used a blend consisting only of Nova Scotian and western Canadian coals. Two other Canadian steel companies have run extensive trials incorporating western Canadian medium- and low-volatile coals in their otherwise Appalachian coal blends. Pacific Rim nations are also purchasing large tonnages of good coking coal from western Canada as well as a weaker coking coal product. The preceding has also shown that many Canadian coals which are, at present, non-commercial resources could be incorporated into non-conventional coking processes to make high-quality cokes. However, coking coals are not classified according to their ability to make coke in pilot or industrial ovens but on results from laboratory tests designed to simulate or relate empirically to the coking process. Standard methods of classifying coals have been based primarily on the experiences of researchers from Europe or the United States with Carboniferous-age coal. Nova Scotian coals fit in well with this classification system. However, many western Canadian coals are good to excellent coking coals but their marketability suffers because classification schemes and models based on laboratory analyses do not demonstrate their coking potential.

The standard methods of classifying coking coals is not based on their coking properties as measured either industrially or in a pilot oven. Coals are classified according to laboratory properties that have traditionally been associated with good coking properties. In North America, the ASTM classification used is based solely on the rank of the coal, either the fixed carbon content (mineral matter free) or the calorific value as shown in Table 24. Generally, high-volatile A, medium-volatile and low-volatile bituminous coals are used to make coke. Other parameters such as volatile matter, vitrinite reflectance, or ultimate carbon content are often substituted as measures of coal rank. In the International classification of hard coal types (Table 25), coals are classified according to rank (volatile matter or calorific value) and then each class is further grouped according to caking properties (FSI or Roga index). The international system allows these caking groups to be sub-grouped according to what is claimed to be coking properties (dilatometer and Gray King tests). The term coking properties used in this context must certainly be a misnomer since the dilatation and Gray King tests do not simulate the heat transfer, particle size consist, or bulk density that occurs in a coke oven and consequently do not represent a measure of coke strength, quality, or cokability of the coal. They might better be termed as another caking index.

Table 24 - ASTM classification of coal by rank

Class	Group	Fixed Carbon Limits, percent (Dry, Mineral-Matter-Free Basis)		Volatile Matter Limits, percent (Dry, Mineral-Matter-Free Basis)		Calorific Value Limits, Btu per pound (Moist,[a] Mineral-Matter-Free Basis)		Agglomerating Character
		Equal or Greater Than	Less Than	Greater Than	Equal or Less Than	Equal or Greater Than	Less Than	
I. Anthracitic	1. Meta-anthracite	98	...	...	2	...	...	nonagglomerating
	2. Anthracite	92	98	2	8	...	...	
	3. Semianthracite[c]	86	92	8	14	...	...	
II. Bituminous	1. Low volatile bituminous coal	78	86	14	22	...	...	commonly agglomerating[d]
	2. Medium volatile bituminous coal	69	78	22	31	...	...	
	3. High volatile *A* bituminous coal	...	69	31	...	14 000[e]	...	
	4. High volatile *B* bituminous coal	...	...	...	...	13 000[e]	14 000	
	5. High volatile *C* bituminous coal	...	...	...	...	11 500	13 000	
						10 500	11 500	agglomerating
III. Subbituminous	1. Subbituminous *A* coal	...	...	...	...	10 500	11 500	nonagglomerating
	2. Subbituminous *B* coal	...	...	...	...	9 500	10 500	
	3. Subbituminous *C* coal	...	...	...	...	8 300	9 500	
IV. Lignitic	1. Lignite *A*	...	...	...	...	6 300	8 300	
	2. Lignite *B*	...	...	...	...	...	6 300	

Table 25 - International classification of hard coal by type

GROUPS (determined by coking properties)			CODE NUMBERS										SUBGROUPS (determined by coking properties)		
GROUP NUMBER	ALTERNATIVE GROUP PARAMETERS		The first figure of the code number indicates the class of the coal, determined by volatile matter content up to 33% V. M. and by calorific parameter above 33% V. M. The second figure indicates the group of coal, determined by coking properties. The third figure indicates the subgroup, determined by coking properties.										SUBGROUP NUMBER	ALTERNATIVE SUBGROUP PARAMETERS	
	Free swelling index (crucible swelling number)	Roga index												Dilatometer	Gray-King
3	> 4	> 45				334 ∇_A	434 ∇_B	534 ∇_C	634				9	> 140	> G_8
													4	> 50-140	G_5-G_8
						333	433	533	633	733 ∇_D			3	> 0-50	G_1-G_4
						332 a	332 b 432	532	632	732	832		2	⩽ 0	E-G
2	2½-4	> 20-45				323	423	523	623 ∇_A	723	823		3	> 0-50	G_1-G_4
						322	422	522	622	722	822		2	⩽ 0	E-G
						321 IV	421	521	621 ∇_B	721	821		1	Contraction only	B-D
1	1-2	> 9-20			212	312	412	512	612	712	812		2	⩽ 0	E-G
					211	311 III	411	511	611 ∇_C	711	811		1	Contraction only	B-D
0	0-½	0-5		100 A / 100 B	200	300	400	500	600	700	800	900	0	Non-softening	A
CLASS NUMBER			0	1	2	3	4	5	6	7	8	9	As an indication, the following classes have an approximate volatile matter content of: Class 6 33-41% volatile matter; 7 33-44% " "; 8 35-50% " "; 9 42-50% " "		
CLASS PARAMETERS	Volatile matter (dry, ash-free)		0-3	> 3-10 / > 3-6.5 / 6.5-10	> 10-14	> 14-20	> 20-28	> 28-33	> 33	> 33	> 33	> 33			
	Calorific parameter [1]		–	–	–	–	–	–	> 13.950	> 12.960-13.950	> 10.940-12.960	> 10.260-10.980			
CLASSES (Determined by volatile matter up to 33% V. M. and by calorific parameter above 33% V. M.)															

Coking models based on laboratory analyses have been developed by many workers to predict coking properties of coals. Most of these models include rank parameter (VM, Ro, etc.), the thermal rheological properties of the coal, and the pulverization and coking conditions to predict coke quality as measured by a standardized drum test. Petrographic models use coal rank and the amount of reactives and inerts observed in maceral counts to predict coke quality. Other models use rank and caking properties to show a window of coal properties suitable for making good coke, such as the values given in Table 3. Some of these models are described below.

PETROGRAPHIC MODELS

This method was introduced in 1957 by Ammosov (58) who suggested that the composition properties of a coal are most completely characterized by the relative concentrations of various maceral groups and the reflectance of vitrinite. These two properties were used to define an index of "leaness" and a coking capacity coefficient to predict cold coke strength. Following the basic concepts of Ammosov's work, Schapiro, Gray, and Eusner (59) developed a method based on grouping maceral types, fusible (reactive) or inert categories, and vitrinite reflectance to predict ASTM stability. Reactive macerals included vitrinites, exinites, resinites, and reactive semi-fusinites (1/3 of the total semifusinite). Reactive macerals were further subdivided into 21 ranges (V types) of 0.1% reflectance. Inert macerals included inert vitrinites (>2.19% reflectance), inert semi-fusinites, micrinites, and fusinites. Empirical relationships were established for the optimum ratio of reactive to inerts for each of the V types and a composition balance index (CBI) defined the ratio of the amount of inerts in a coal to the optimum. In addition, a strength index was introduced to quantify the relationship between optimum coke strength for the rank of coal and the amount of inerts present. ASTM stability factor is predicted from the CBI and strength index.

Many investigators have made modifications to the Schapiro and Gray method to improve coke quality predictions. For example, Thompson and Benedict (60) made modifications to the Shapiro and Gray method by suggesting that the inertness of the semifusinite varied with rank and the semi-fusinites of low-volatile coals were more inert than high-volatile coals. Stein and Smith found for South African coals that the fusing capacity of vitrinites decreased markedly when its mean maximum reflectance exceeded 1.49% and was completely inert above 1.89%. Reactive semi-fusinites were considered to be those having reflectances less than the vitrinite reflectance plus 0.6%. The authors made empirical determinations and devised a method to predict the M_{40} index.

METHODS BASED ON THERMAL RHEOLOGICAL PROPERTIES

A number of models use thermal rheological properties plus a rank parameter to predict the quality of coke produced from coal. Many models also contain carbonization parameters such as pulverization level and coking rate, etc. Most of the models developed in Europe include dilatation as the thermal rheological property and volatile matter as the rank parameter. Models developed in Japan use fluidity as the thermal rheological index and vitrinite reflectance as the rank parameter, although other models have used other caking and rank parameters.

The G-Factor method developed by Simonis (61) predicts M_{40} coke strength, assuming that coke quality can be determined by VM, the volatile matter in the coal; G, the cokability of a coal; M_S, the particle size distribution factor; and K, the specific heating factor. The G factor is determined from the dilatation curve according to the equation:

$$G = \frac{E+V}{2} \cdot \frac{c+d}{cV+dE}$$

where c is % contraction, d is % dilatation, and E and V are the temperatures of initial contraction and dilatation, respectively.

The G-factor approach was thought to be a good predictive method since all parameters were believed to be additive for German coals. However, the additivity of the G factor is limited when considering a blend of two or more coals whose plastic ranges do not overlap sufficiently (62).

The National Coal Board, U.K., modified the G-factor approach because it gave poor coke strength predictions for British coals with volatile matter contents greater than 34% (63). Using the results from charges carbonized in a 250 kg test oven, the following equation was derived involving T, carbonization time to 900° C in a 460 mm wide oven; VM, the volatile matter content of the coal; and G factor as defined above:

$$M_{40} = 103.9 + 24.8xG - 1.196 \times 10^{-6}\, V^5 + 2.57\,\frac{V^2}{T} - 88.04\,\frac{V}{T}$$

Czechoslovakian investigators (64) found that the G-factor approach did not work well with their coals and suggested an alternative approach using two thermal rheological parameters, FSI and dilatation, as well as coal VM and particle size distribution. Through regression analyses, M_{40} and M_{10} coke strengths can be predicted from these coal parameters.

Japanese workers have used a very simple model for blend composition to determine if it is suitable for coke making (65). This model gives a plot of volatile matter versus total dilatation (c+d) of coal. To make suitable coke for the blast furnace, the total dilatation of the coal must be between about 70 and 140% and the volatile matter content between 30 and 33%. The National Coal Board has developed a similar diagram based on total dilatation as the caking index but with

a slightly larger window on coal properties for making good coke with a volatile matter range between about 23 and 32% and a total dilatation between 50 and 150% (66,67).

Several methods have been developed in Japan to predict coke quality based on vitrinite reflectance of the coal and Gieseler fluidity. Sunami incorporated the fluidity of vitrinites into a petrographic model to correct optimum inert levels and improve coke quality predictions (68). This model improves predictions for Canadian and Australian coking coals by lowering their CBI indices to values nearer the optimum.

Suginobe developed a diagram used at Kawasaki Steel Corp (69) to predict JIS tumbler strengths based on the logarithm of maximum fluidity and a factor (ϕ). The factor, ϕ, is a function of vitrinite reflectance, total reactives, charge bulk density, and carbonizing rate.

The MOF diagram is a simple approach developed by the Nippon Kokan Keihan Corp. to meet coking coal blend specifications (70). The diagram shown in Figure 17 plots fluidity on a logarithmic scale on the y axis versus Ro on the x axis. A window in the diagram shows that coals must be blended to meet fluidity specifications of 200-1000 ddpm and Ro between about 1.2-1.3 to achieve DI^{30}_{15} of 92.0. A second window in the diagram shows the coal blending region can be extended significantly if partially briquetted charges are carbonized.

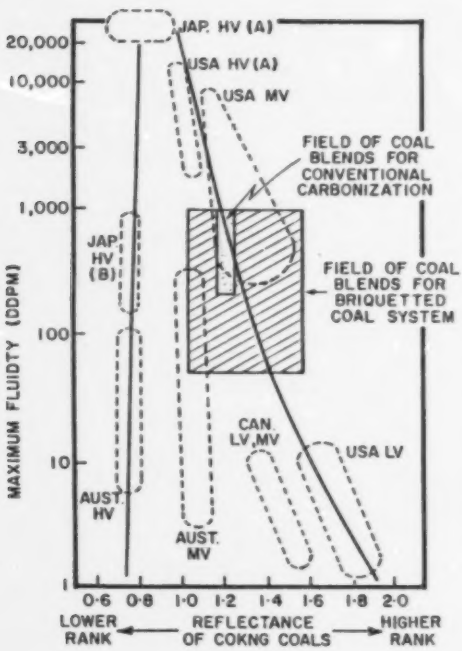

Fig. 17 - Fluidity of bituminous coals vs rank, showing acceptable range of coal properties for conventional and 30% partially briquetted charges; after Miyazu et al.(68).

The diagrams also show the range of coal properties considered typical for Canadian production coals. More recently, these authors have modified the prediction methods and have incorporated coke-inert specifications upon their blends.

Based on the number of different models described above, it would appear that none of the approaches can be considered as universal. Most of the above models have been developed in Europe or the U.S.A. on coals of carboniferous origin on relatively limited databases. Several of the above methods were compared by changing coal rank and caking properties to common bases, i.e. vitrinite reflectance and total dilatation, respectively (71). Coal petrographic properties were converted to total dilatations based on formulas derived by van Krevelen (72,73). Gieseler fluidity and G factor proved to be related to total dilatation by logarithmic relationships. The relationship between c+d and fluidity is shown in Figure 18 while c+d is related to G factor by the equation:

$$G = 0.709 + 0.0716 \ln (c+d)$$

Figure 19 is a plot of several methods, after conversion of data to a common base, of total dilatation and Ro. It shows that the windows for many of these models overlap and occur in areas of high coke stability. Although there are some

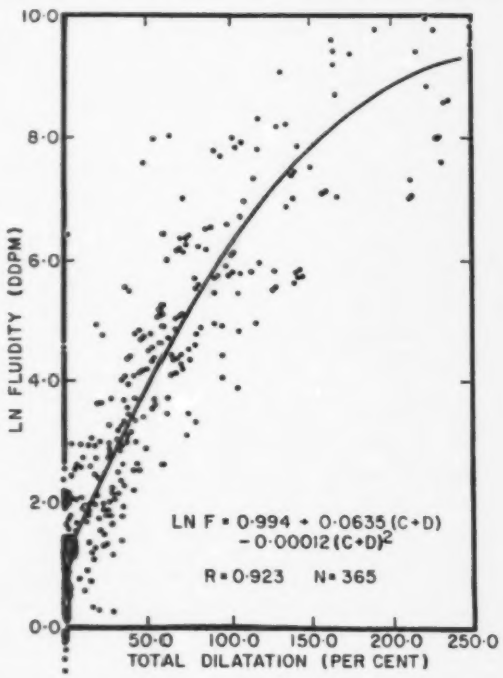

Fig. 18 - Plot showing relationship of natural logarithm of fluidity vs total dilatation (CANMET data)

differences between the size of the windows for the various models, the figure suggests that at this level at least, the models predict similar results. However, for cokes made from many western Canadian coals, the predictions of coke

strength using the above models were generally low compared to pilot oven results. Regression of actual coke strength versus the predicted results from the various models gave rather poor correlations, with large standard errors. The models, developed mainly from data on Carboniferous coals, do not apply well for Cretaceous western Canadian coals. This is particularly true for models based on dilatation properties.

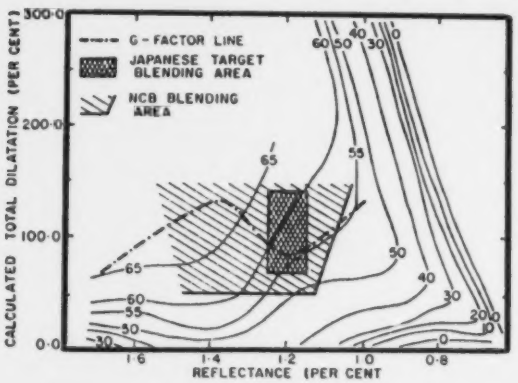

Fig. 19 - Comparison of various models used to predict coke strength

CANMET PETROGRAPHIC MODELS FOR CANADIAN COALS

Petrography is probably the most common method of studying coal for coking purposes. The method is particularly useful because it can analyze small samples, is adaptable to a high degree of automation, and can provide a meaningful analysis of samples that have unmeasurable dilatation or Gieseler fluidities. The analysis readily determines the rank and proportion of macerals in a coal. Extensive petrographic analyses at CANMET have shown that the coals from western Canada have quite different micro litho-types and maceral compositions in comparison to similar rank Carboniferous coals. Western Canadian coals generally have higher inert maceral contents, with much higher semifusinite but lower micrinite and exinite levels, than Nova Scotian coal or other Carboniferous coals from North America. However, the ability of petrography to predict coke quality is to some extent still considered an art dependent on the operators' interpretations and identification of macerals. Although instruments to automatically measure coal maceral reflectances are widely used for quality control purposes, at present, predictions of coke strength results from automated histograms are considered unreliable, and coke quality predictions are still done by subjective manual or semi-automated methods. For example, in a round-robin evaluation of a western Canadian coking coal carried out by the European ICCP and the CCPG, results showed considerable variation in maceral identifications between the 29 laboratories (the quantity of vitrinite, the most easily identified maceral, varied from 47% to 74% among the laboratories). Based on the results of this round-robin, it was estimated that the inter-laboratory standard deviation for an ASTM coke stability prediction was 7.6% for this particular coal based on a standard Shapiro and Gray interpretation of results (74).

Assignment of the level of reactive semifusinite is also a major problem, particularly for the western Canadian coals that tend to have much higher levels than Appalachian coals. The Schapiro and Gray method assigns one-third of the semifusinite as reactive, but CANMET found this method frequently predicted results that were lower than observed coke strengths, particularly for coals with higher proportions of semifusinite (Fig. 20). As a result, CANMET developed a modified procedure (75) to be used when the total semifusinite was greater than 20%. For these cases, better results were obtained by taking one-half of the semifusinite as being effectively reactive and by using the original Shapiro and Gray table of U.S. Steel for optimum inerts in the calculation. Over the past 10 years, this technique for coals has become the CANMET standard and predictions in CANMET's database for various coals can be compared on a common basis. Still, there is some bias between the test oven and predicted stabilities with CANMET's database. With the introduction of micro-computers into the laboratory, CANMET did petrographic back calculations to estimate the amount of semifusinite that must be considered as reactive to obtain the correct (test oven) stability. The calculations showed that the amount of semifusinite that was effectively reactive in western Canadian coals was on average about 45% based on the CANMET approach, but that this value could change considerably (from a few percent to 100%) depending on the coal. Nandi and Montgomery, using a hot stage microscope, found that the semifusinites having low reflectance in western Canadian coal were reactive macerals and had melting points lower

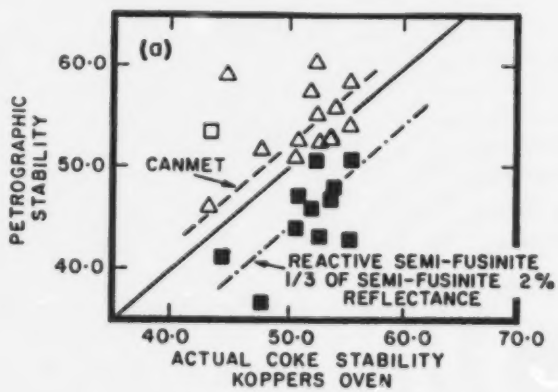

Fig. 20 - Comparison between actual coke stability from Koppers test oven and predicted coke stability using one-half reactive semifusinite (CANMET) vs one-third reactive semifusinite

than that of the corresponding vitrinite in the coal (76). The proportion of such low reflecting semifusinite varied from coal to coal. As a result, a method was developed to predict a "cut-off" reflectance value that would separate reactive from the inert macerals in a random reflectogram of all coal macerals. Petrographic coal pellets were examined from 61 bulk coal samples carbonized in CANMET test ovens (77). Maximum reflectances were measured on the vitrinite macerals and random reflectances measured on all macerals during a maceral count. Petrographic back calculations on each sample gave the percentage of inerts in the sample, from which a random reflectance cut-off line was calculated. A regression of Ro max versus R cut-off for the 61 coal samples gave a good correlation (r=0.92). Thus, the reflectance of the random cut-off can be predicted from Ro max by the equation:

$$R_{cut\text{-}off} = 0.987\ R_{o\ max} + 0.236$$

By this method, the amount of reactive semifusinite can vary from coal to coal. The % inerts can be readily determined by computer from the histograms, and ASTM coke strength can be calculated from this information by standard petrographic methods. It must be emphasized that the reactives and inerts are still only effective values since they depend on the method of (back or forward) calculation (e.g. whether exinites and semifusinites are prorated into the vitrinite groups or assigned actual random reflectance values).

CANMET is currently evaluating this and alternative approaches, both in-house and under contract research, in an effort to further improve predictions of coke quality based on petrography. One such approach is to carbonize the coal in a tube furnace and analyse the coke microscopically to identify the actual amount of inert macerals, and then predict coke strength and perhaps CSR from coke reactive/inert and textural properties.

CANMET MODELS USING THERMAL RHEOLOGY

CANMET, using its western Canadian coal database, attempted to develop more pertinent relationships between coke quality and western Canadian coal properties as measured in the laboratory. Three thermal rheological properties of FSI, Ruhr dilatation, and Gieseler fluidity for the coals and the rank parameters of Ro max and volatile matter were used. Figure 21 is a MOF-type plot showing the placement with respect to rank and caking properties of the western Canadian coals in the database. All ranks of coking coals (hv to lv bituminous) exist in western Canada with Ro's ranging from 0.78-1.75 in the database. Although none of these exploration and production coals have maximum Gieseler fluidities comparable to the Nova Scotian hv coal (about 27 000 ddpm), the figure shows that the western Canadian coals have a wide distribution of Gieseler fluidity (0-6000 ddpm), with maximum fluidity occurring at a vitrinite reflectance of about 1.0, consistent with coking coals from other parts of the world. Still, the majority of production western Canadian coals have fluidities and other caking properties that are considered low relative to the carboniferous coals of Europe and North America.

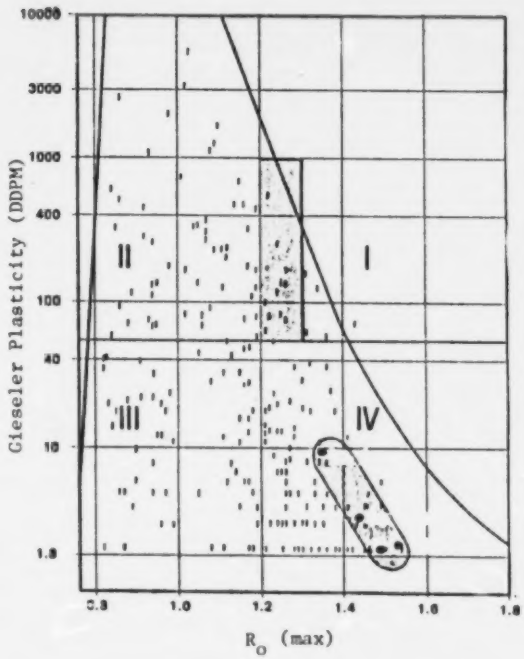

Fig. 21 - Vitrinite mean maximum reflectance and Gieseler fluidity results of western Canadian bituminous coals

Figures 22 to 25 show the influence of dilatation, fluidity, and FSI on coke quality parameters obtained from movable wall coke oven tests done at CANMET. Figure 22 shows plots of JIS drum indices versus the total dilatation measured on CANMET's Ruhr dilatometer for coals from the database. The models described above would suggest that total dilatations should be at least 50-70 to make strong cokes. Figure 22 shows that many western Canadian coals with total dilatations of 0, and hence G factors of 0, can make strong cokes having JIS DI_{15}^{30} and JIS DI_{15}^{150} greater than 93 and 83, respectively. This figure also shows that some coals from western Canada with total dilations of 0 make weaker cokes. Figure 23 shows a histogram of the ASTM stabilities from coals in the database that have c+d and G factors of 0. About 20-25% of these coals make coke with an ASTM stability of at least 50. Consequently, it appears that the dilatation measurement is a very poor tool to distinguish the good from the weak coking coals of western Canada.

Figure 24 includes several plots of different measures of coke strength versus Gieseler fluidity. Although fluidity appears to be a better measurement than dilatation for western Canadian coals, the figure shows there are a few coals that make strong coke with maximum fluidities of 1 ddpm or less and many coals in western Canada that make strong coke with fluidities less than 10 ddpm. All plots show that many western Canadian coals, having Gieseler fluidity properties considered less than desirable by most prediction

theories, can be carbonized to make high-strength coke. In fact, based on the JIS DI^{30}_{15} and the ASTM hardness results, it would appear that optimum coke strength would occur at fluidities between 10 and 100 ddpm.

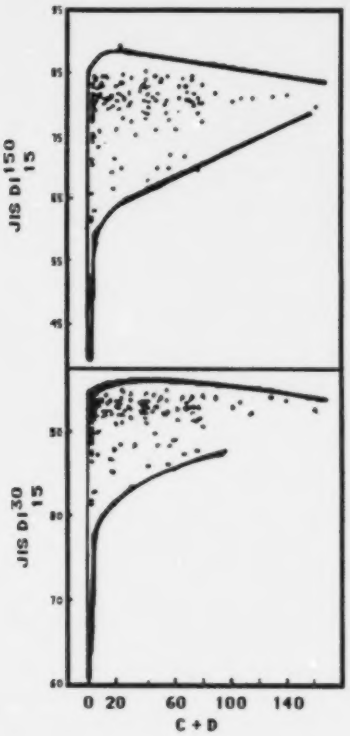

Fig. 22 - Plot of JIS DI's vs total dilatation for western Canadian coals showing coals with dilatations of 0 can have high coke strengths

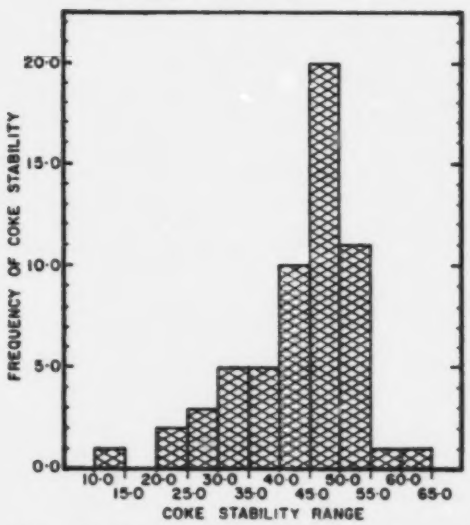

Fig. 23 - Histogram showing ASTM stability of cokes made from western Canadian coals with total dilatations of 0

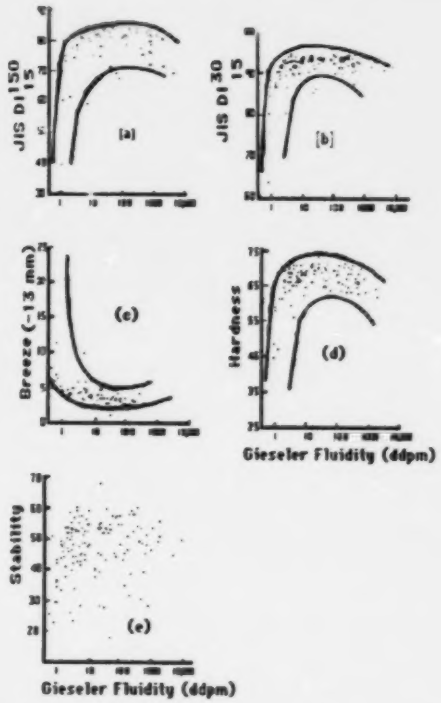

Fig. 24 - Influence of coal Gieseler fluidity on coke quality parameters

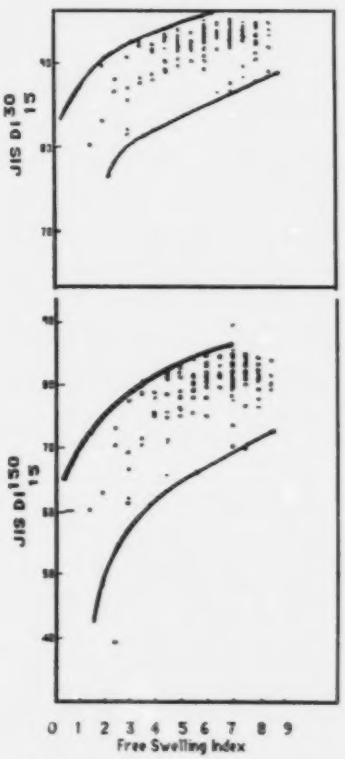

Fig. 25 - Effect of FSI on coke quality parameters

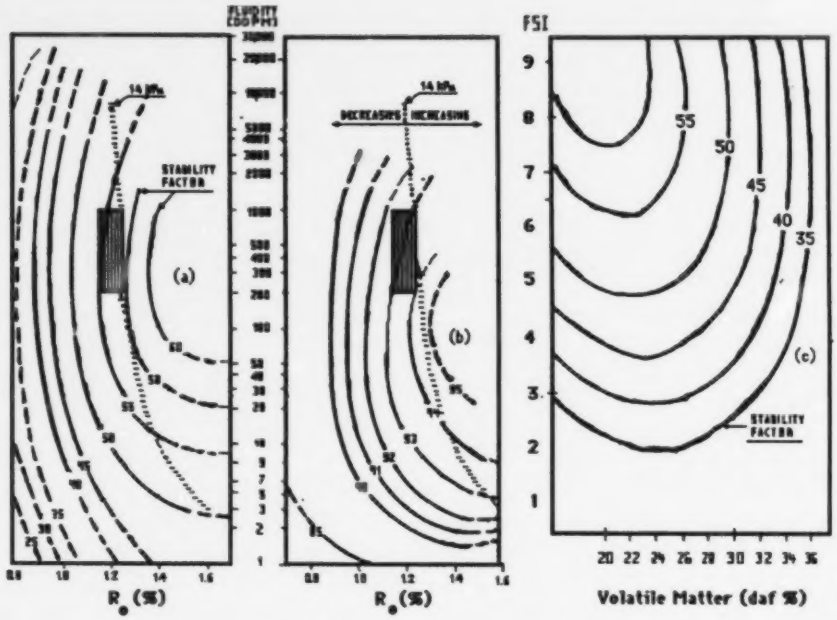

Fig. 26 - Influence of western Canadian coal rank and caking properties on resulting coke strength (a) ASTM stability vs Ro and Gieseler fluidity (b) JIS DI 30/15 vs Ro and Gieseler fluidity (c) ASTM stability vs VM and FSI

Figure 25 shows plots of FSI versus the two JIS drum indices for CANMET's database. Although there is considerable range in the drum indices for a given FSI, there appears to be a gradual relationship between FSI and coke quality (i.e. low FSI coals generally made poorer coke while coals with poor Gieseler or dilatation results did not necessarily make poor coke). As a result, the FSI seems to be a better overall parameter to evaluate the coking potential of an unknown coal from western Canada than dilatation or Gieseler fluidity.

Three relationships established for western Canadian coals based on thermal rheological and rank properties are shown in Figure 26. Although the FSI/VM plot is not as reliable as the Gieseler/Ro plots for predicting cokes of high strength, they gave the minimum overall standard error for all coals in the database, presumably because the low FSI results are more meaningful than low Gieseler fluidity or dilatation numbers. The Gieseler fluidity/Ro plots show that quite strong cokes can be made from medium-/low-volatile western Canadian coals having fluidities as low as 10 ddpm. All the models are limited since standard errors for the models were still quite large, probably caused by the nature of the database. The database consisted of about 180 coals, not all from producing mines or mines near commercial production. Some were adit samples, some were uncleaned, others were cleaned to uneconomically low ash levels, while others were probably severely weathered. Despite the limitations of the database, these models have been quite successful in estimating coke quality for coals or blends containing Canadian coals (27). However, results from some programs, e.g. the large changes in coke quality caused by removal of small quantities of ash (Table 12) cannot be entirely explained by the changes in thermal rheological properties of Figure 24 and other reasons such as coal and ash size consists must be considered.

FACTORS AFFECTING THE THERMAL RHEOLOGY OF CRETACEOUS WESTERN CANADIAN COKING COALS

Coking coals are classified according to rank and thermal rheological properties measured in the laboratory as described above. However, it is the plastic coal to coke transformation in a real coke oven that is critical to coke structure and strength and not the apparent thermal rheological properties as measured in the laboratory. It has been assumed that the relationships between the apparent rheological properties as measured in the laboratory and those in a coke oven hold for all coals. It has become apparent that for a certain percentage of western Canadian coals having very low dilatations or Gieseler fluidities that these relationships do not necessarily hold.

An investigation was undertaken to determine if the low thermal rheological properties of western Canadian coals are caused by methods that were developed originally for carboniferous coals (78). A second objective was to identify the source of any differences in the thermal rheological properties between Appalachian and western Canadian coals.

Standard and non-standard Ruhr dilatation, Gieseler fluidity, and FSI tests were done on six Appalachian carboniferous and nine western Canadian cretaceous coals having Ro fairly evenly distributed, 0.90-1.43 and 0.91-1.59, respectively. Several of the coals were subjected to stage crushing and specific gravity (SG) separations for rheological, petrographic, and chemical analyses. Finally, SG fractions of a western Canadian coal were blended to match the size consist, analytical and petrographic properties of an Appalachian coal having similar rank (Ro).

Many investigators (71) have shown that larger particle sizes and higher heating rates can increase coal swelling properties. In this study similar work was done to compare the two coal types, using dilatation in particular to determine whether alternate test conditions would rate the coking properties more fairly.

Two heating rates, 3 and 4.5°C/min, were employed in the dilatation experiments. The particle top sizes were 150, 425, 850, and 2360 μm. Nine western Canadian and six Appalachian coals (and many of their sp gr fractions) exhibited significant increases in c+d (contraction decreased but dilatation increased) and G-factor with increasing top size. Figure 27 shows the effect of top size on the dilatation curves of a western Canadian coal having relatively good dilatation characteristics (79). The improvement in the dilatation properties for both western Canadian and Appalachian coals decreased toward the higher top sizes as shown in Figure 28. Higher heating rates also resulted in a significant rise in both the total dilatation and the G-factor. The combined effects of increased top size and heating rate further enhanced dilatation. Figure 29 plots the dilatation results from the standard Ruhr dilatation test (x-axis) versus all non-standard dilatation tests done on several western Canadian coals and sp gr coal fractions using larger top sizes and heating rates. Figure 30 shows a similar plot for the Appalachian coals. The figures show that the greatest relative improvement to dilatation was for the western Canadian coals exhibiting c+d≤10%; truly non-coking coals would be expected to show little improvement. However, even though the rheology of the western Canadian coals could be increased by raising the top size and increasing heating rate, Figures 29 and 30 show that c+d remained significantly lower than those of Appalachian coals.

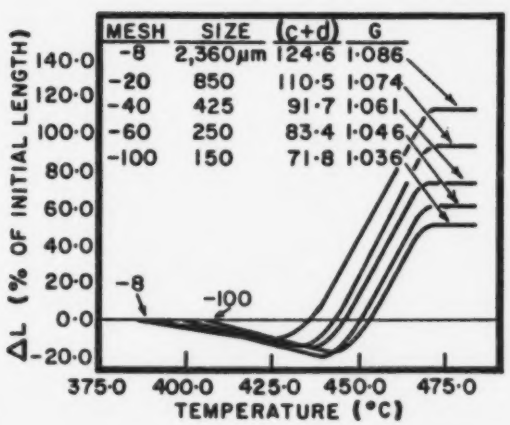

Fig. 27 - Effect of particle size on the dilatation of a Western Canadian mvb coal [after Ramachandran (79)]

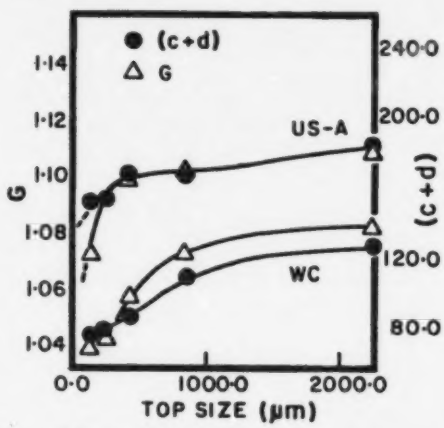

Fig. 28 - Effect of particle top size on (c+d) and G factors for a mvb western Canadian and U.S. coal at a heating rate of 4.1°C/min (79)

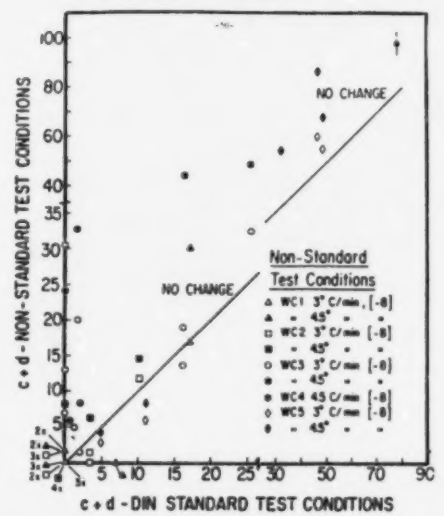

Fig. 29 - Effect of changing from standard Ruhr to non-standard conditions on the dilatation properties of different wash fractions of five western Canadian coals

Tests on 60 mesh samples but with the -100 mesh material removed from three western Canadian and two Appalachian samples suggested that fines may inhibit contraction and dilatation. All coals' than the dilatation test. More importantly, the FSI values are quite similar for the two coal types although the Appalachian coals are slightly larger, and would probably compare more favourably with the actual coke strength results from the two coal types (not determined in this investigation).

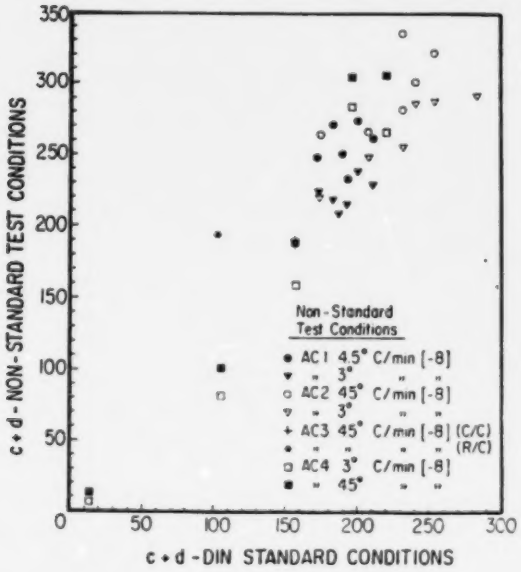

Fig. 30 - Effect of changing from standard Ruhr to non-standard conditions on the dilatation properties of different wash fraction of four U.S. coals

c+d values at -8 mesh and -60 x 100 mesh were similar. Increasing the heating rates for the -60 x 100 mesh samples to 4.5°C/min increased c+d similarly to increases observed for the -8 mesh samples at the same heating rate. Apparently, the main effect of raising the top size to -8 mesh is to reduce the fraction of the 100 mesh material in the samples.

Table 26 shows the effect of particle size on the FSI of three western Canadian (Ro, 1.14-1.59) and three Appalachian coals (Ro, 1.0-1.43). FSI is relatively insensitive to particle size, presumably caused by the higher heating rate rather

The effects of petrographic composition on the standard rheological properties were compared for all coals. Additional samples having artificial petrographic compositions were also generated through sieve and SG separations on four western Canadian and three Appalachian coals. Concentration plots of each maceral type versus percent vitrinite for all coals showed that the Appalachian coals generally had higher micrinite, exinite, and vitrinite contents. For SG samples having low vitrinite, western Canadian coals had much higher semifusinite than Appalachian coals. At vitrinite levels above 70%, the semifusinite levels became more similar. Still, after normalizing each coal to 70% vitrinite, western Canadian coals had consistently higher semifusinite and lower micrinite as shown in Figure 31. Microlithotype analyses varied considerably but generally reflected the maceral differences in the two coals. Western Canadian cretaceous coals had less clarite and durite and generally more inertinite than the Appalachian coals.

Figure 32 shows total dilatation plotted against the vitrinite content for the various SG and size consist fractions from six western Canadian and four Appalachian coals. It shows that c+d is coal specific but is low for both western Canadian and Appalachian coals at less than 30% vitrinite content. As vitrinite increased to 60%, the c+d values of the Appalachian coals increased quickly to 150-300% while those of western Canadian coals increased slowly, and some coals with 50% vitrinite still had zero dilatation. Maximum dilatation for any of the western Canadian coals was about 100% at a vitrinite content of 75%, about half the magnitude of the Appalachian coals. Figure 33 shows Gieseler fluidity gives similar trends with vitrinite content for the two coal types; fluidities for the western Canadian coals were 10-200 ddpm compared with 200-10 000 ddpm for the Appalachian coals at similar vitrinite contents (60-80%). FSI values became more similar for the two coal types, with values approaching 8-9 as vitrinite contents approached 80%.

Table 26 - FSI as a function of top size for three western Canadian and Appalachain coals.

Coal	Top Size 2360 µm	850 µm	425 µm	250 µm	150 µm
WC 1	-	5.5	-	5.5	-
WC 2	6.5	6	6	6.5	7
WC 3	-	5.5	-	5.5	-
AC 1	-	7.5	-	7.5	-
AC 2	7	6.5	7	8	8.5
AC 3	-	7.5	-	8	-

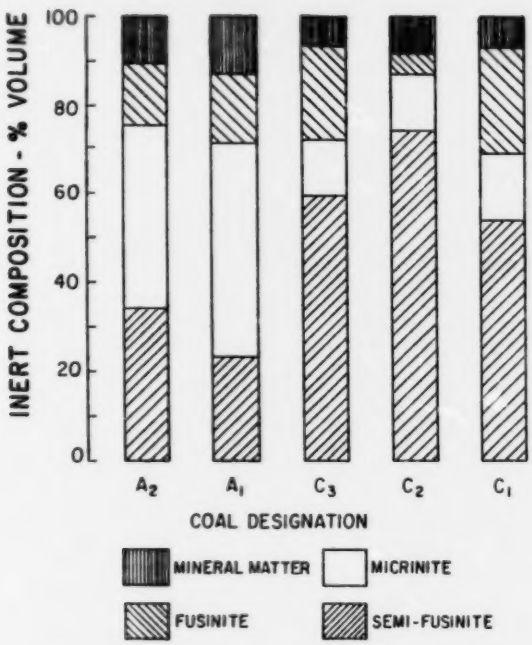

Fig. 31 - Relative proportions of the different inerts in western Canadian and Appalachian coals normalized at a 70% vitrinite concentration

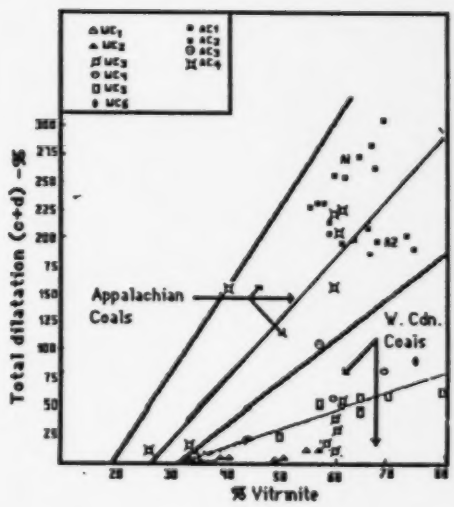

Fig. 32 - Effect of a change in vitrinite content on the total dilatation of western Canadian and Appalachian coals

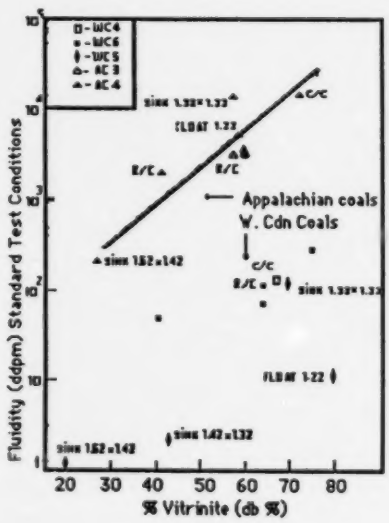

Fig. 33 - Effect of a change in vitrinite content on the Gieseler fluidity of western Canadian and Appalachian coals

Dilatation properties of an Appalachian and western Canadian coal having identical ranks (Ro of 1.22 for both coals) are compared in Figure 34. The figure compares c+d as a function of vitrinite content for several SG and size fractions of the two coals. Surprisingly, the differences between c+d for the two coal types became larger as the vitrinite content increased toward 100%.

For the two similarly ranked coals shown in Figure 34, various SG fractions (at a given size consist) of one coal were blended using linear program models to match various proximate and petrographic parameters in the other coal. Eight blends were used to target vitrinite, ash, sulphur, inertinites, microlithotypes, vitrinite/semifusinite, and vitrinite/fusinite ratios in 8x35 and 35x60 mesh size consists. The best overall petrographic match was achieved by targeting ash and inertinites of the 35x60 mesh size fraction of the AC coal. Comparison of analytical results showed excellent matching of macerals as shown in Table 27. Coke strength predictions from petrography would be for both of these samples. Dilatation results for the two samples are totally different, but FSI's are more similar and more in agreement with the petrographic prediction.

Table 28 shows that the 8x35 mesh fractions of the 1.32x1.22 SG fractions for the two coal types had nearly identical microlithotypes. Still, the dilatation results from this and the other blend matches showed the western Canadian coals consistently had c+d values 25-50% of those of the Appalachian coals; Gieseler fluidities showed similar trends although fewer analyses were done. FSI results for the nine pairs of matches were almost the same, averaging 8.5 for the Appalachian coals and 8 for the artificially matched western Canadian coals.

What causes these differences in dilatation and Gieseler fluidity of western Canadian and Appalachian coals even when their petrographies are similar? Pulverization of friable western Canadian coals for dilatation could degrade the large (and abundant) semifusinite into fine inert particles interfering with interparticle fusion and swelling. The micrinite in the Appalachian coal is more finely dispersed naturally, and pulverizing to -60 mesh may not release them to interfere with interparticle fusion and gas entrapment that promotes swelling. However, c+d on 60x100 mesh samples, although larger than for the -60 mesh samples, showed about the same amount of improve-

Table 27 - Matching of macerals of a western Canadian and Appalachian coal of the same rank

	Coals	
	AC4 (-35x60) 1.32x1.22 SG	WC5 (-35x60) blend of SG
Maceral analysis (%)		
Vitrinite	59.5	61.2
Exinite	2.8	0.7
Semifusinite	20.0	21.4
Fusinite	4.2	6.5
Micrinite	9.4	5.6
Mineral matter	4.1	4.5
Chemical analysis		
Sulphur	0.82	0.45
Ash	7.8	7.8
Thermal rheology		
C+D %	183	35
FSI	8.5	7

Table 28 - Matching of microlithotypes of a western Canadian and Appalachian coal of the same rank

	Coals	
	1.32 x 1.22 sp. gr.	
	AC4	WC5
Microlithotype, %		
Liptite	-	-
Clarite	2	-
Vitrite	38	43
Vitrinertite	43	41
Inertite	14	12
Trimacerite	3	4
Durite	-	-
Thermal Rheology		
c+d	256	60
FSI	8.5	9

ment for the two coals. Also, the range of BET surface areas (0.1 -1.6 m^2/g) overlaps for the suite of Appalachian and western Canadian coals and cannot explain the differences in dilatation. Preferential oxidation of the western Canadian coal samples over the Appalachian coals prior to or during the study was considered as a possible cause of the differences in their dilatations and Gieseler fluidities. Aging experiments on three western Canadian and two Appalachian coals showed that both standard and non-standard dilatations of the western Canadian coals decreased slightly with time over the course of this investigation, even though all samples were freshly mined and stored under vacuum refrigeration. Still, deterioration for any of the coal was minor since the G-factors showed almost no change over a three month period.

Differences in biological and geological histories of the western Canadian and Appalachian coals appear to have resulted in fundamental differences in plastic properties of their vitrinites as measured by dilatation and Gieseler fluidity. Figure 34 shows that the differences in c+d between Appalachian and western Canadian coals actually become larger as the vitrinite increased. CANMET has shown in an analysis of its database on western Canadian coals (71) that these coals had lower volatile matter content than that found by most other researchers for carboniferous coals of the same vitrinite reflectance; this is consistent with the coals being sub-hydrous in nature that results from maturation under a non-marine cover. It was assumed, until now, that the lower volatile matter contents of the Cretaceous coals was caused solely by their high inertinite (semifusinite) content (80).

Perhaps some of the differences could be caused by differences in the chemistry of the vitrinite. Sunami, in a study on concentrated vitrinites, has also suggested that vitrinites of the same rank can have quite different Gieseler fluidities (68). Figures 35-37 show plots of the carbon, volatile matter, and hydrogen content versus vitrinite content for the SG fractions of the western Canadian and Appalachian coals having the same vitrinite reflectance. Figure 35 shows the carbon content of the two coals is very similar indicating they are of similar rank. Figure 36 shows the VM of the Western Canadian coal is lower than the corresponding Appalachian coal even when extrapolations are made to the pure vitrinite level. Figure 37 also shows that the western Canadian coal contains fractionally less hydrogen than the Appalachian coal (5.0 vs 5.2%). This is consistent with the lower VM content. Chemical differences in the vitrinites of western Canadian coals could contribute to their unusual behaviour in dilatation and Gieseler fluidity tests.

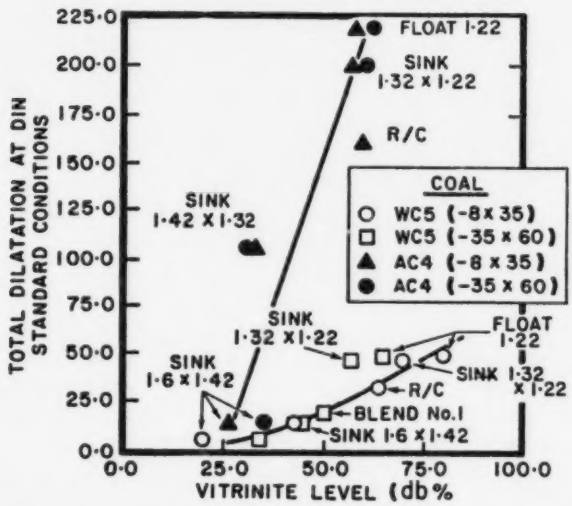

Fig. 34 - Effect of a change in vitrinite content on the total dilatation of a western Canadian and an Appalachian coal of the same rank

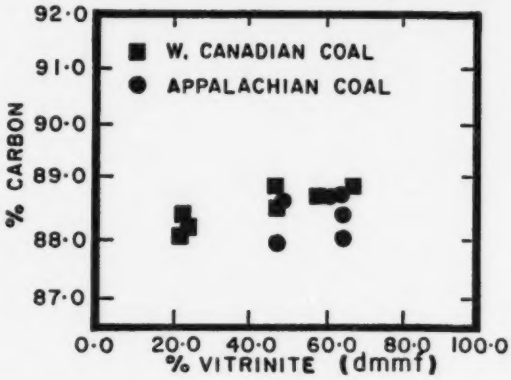

Fig. 35 - Carbon vs vitrinite for various specific gravity fractions of a western Canadian and Appalachian coal having the same rank (Ro)

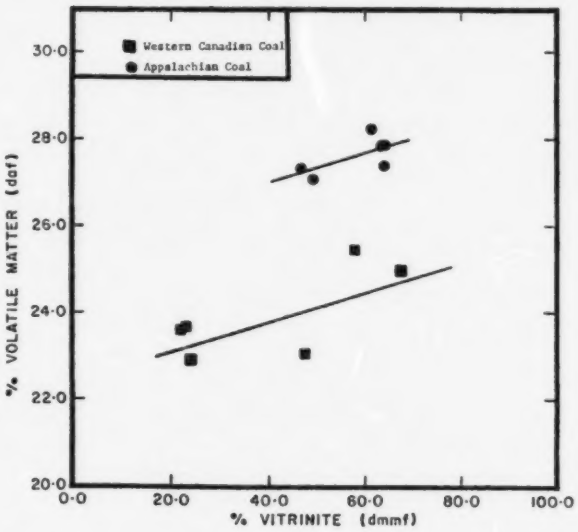

Fig. 36 - Effect of vitrinite content on volatile matter content of s.g. fractions from an Appalachian and western Canadian coal of the same rank (Ro)

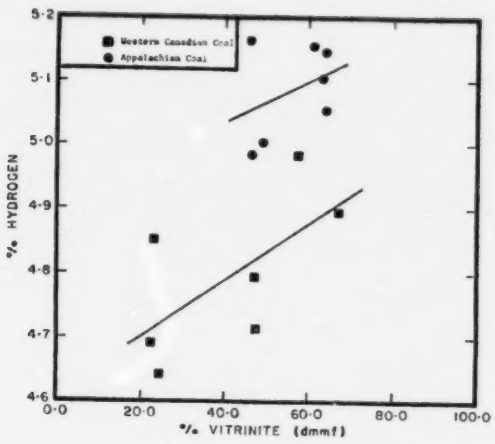

Fig. 37 - Effect of vitrinite content on hydrogen content of s.g. fractions from an Appalachian and western Canadian coal of the same rank (Ro)

During an investigation on several ranks of western Canadian and Appalachian coals and cokes, microscopic analyses of the cokes showed that the relative amounts of anisotropic textures (i.e. the material in the coke formed from only the macerals in the coal that fuse) were about the same for similar ranks (Ro) of the two coal types (Fig. 38). This suggests that any chemical differences in the reactive macerals in the coal are not transmitted into textural differences in the coke during carbonization. Apparently, the textures of the plastic phase at resolidification temperatures are quite similar for similarly ranked coals from western Canada and Appalachia.

Again, the above FSI results, which were similar for western Canadian and Appalachian coals with similar petrographic properties, are more consistent with coke quality than the Ruhr dilatation or Gieseler Plasticity test. As discussed previously, coke strength indices from CANMET's database on western Canadian coals gave better overall correlations with FSI and coal rank properties than Gieseler fluidity and rank properties, and much better correlations than Ruhr dilatation models. It appears that the higher heating rates of the FSI test are generally better for more fairly comparing coking properties of western Canadian cretaceous coals with the Carboniferous coals. Still, a better test than the crude FSI test is needed because the standard error of the correlations is not good. Perhaps other existing test procedures such as the specific swelling index, the Roga, Sapozhnikov, or plastofrost tests would be better; or perhaps a dilatometer using even higher heating rates than those examined here would more accurately reflect the real and relative plastic and coking properties of all coals.

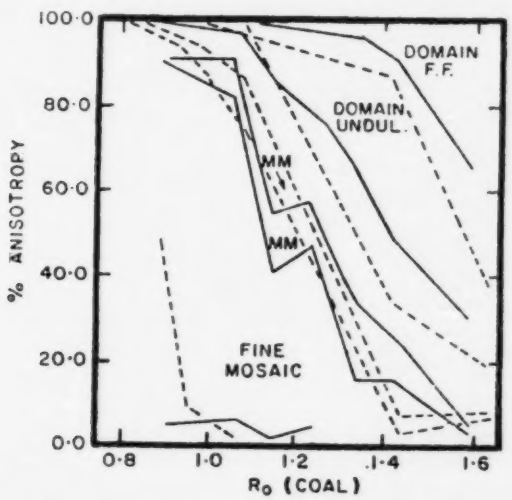

Fig. 38 - Comparison of amounts of anisotropic textures in cokes from various ranks of Appalachian and western Canadian coals

Duever has shown by microscopic examination of the coal-semicoke transition of samples from the plastofrost instrument (which simulates the heat transfer in the coke oven by unidirectional heating) that a western Canadian coal behaved quite similarly to an Appalachian coal of similar rank but had a wider temperature range of coal grain fusion (81). Perhaps volatile matter is emitted through the plastic layer in Appalachian coals in a much narrower temperature (and time period), resulting in higher swelling and gas pressures. Decomposition of western Canadian coal may occur over broader temperature ranges, resulting in good coke from increased time of contact between inert and fused materials.

CANMET is continuing both in-house and contract research in this area in an effort to explain the thermal rheological properties of all coals and to adopt or develop an instrument that can be universally applied.

EFFECT OF STORAGE ON THE LABORATORY AND COKING PROPERTIES OF CANADIAN COALS

Since coal is still marketed according to specifications for various thermal rheological parameters, investigations were carried out at CANMET to determine the effects of storage time on the coking coal properties. Delays in preparation and testing of a coal when stored in bottles or barrels may give quite different results than would be obtained from samples of the coal as mined or samples from large stockpiles where oxidation is minimized.

In an initial investigation to quantify changes to coke quality with storage time in drums, a western Canadian coal having low thermal rheological properties was used. The coal (as received) had an FSI of 4, max. fluidity of 2, a total dilatation of zero, and a Ro of 1.10 (37). However, ASTM stability of the coke changed from a value of about 40 at the time of receipt to about 32 after 10 weeks' storage in barrels. Deterioration was minimal between 10 and 39 weeks of storage.

In a more detailed investigation on the effects of coal storage time and temperature on the caking and coking properties of coal, twelve drums of a good coking medium-volatile western Canadian coal (slightly higher rank with Ro of 1.18) were split upon receipt into four portions (82). One portion was carbonized immediately in CANMET's Carbolite test oven; second and third portions were carbonized respectively after 4 and 20 weeks' storage in sealed barrels at ambient temperatures. The fourth portion was carbonized after 20 weeks' storage under refrigeration to determine if refrigerating the samples reduced any tendency toward oxidation. Thermal rheological tests were done periodically during the 20 week period on samples stored at ambient temperatures. Figure 39 shows the effects of storage time on the thermal rheological properties of this coal. Gieseler fluidity (and to a lesser extent dilatation) decreased quickly for the first 5-8 weeks and moderately thereafter until 20 weeks of storage. Neither storage time nor refrigeration of samples caused any deterioration of the ambient strength properties of the coke (Fig. 40). In fact, ASTM stability and JIS indices improved slightly, as did the FSI indices. However, Figure 41 shows the coke CSR properties deteriorated over the 20 week period for coal samples stored at ambient or reduced temperatures. Apparently, coke CSR is a much more sensitive parameter to oxidation than coke strength parameters measured at ambient temperatures.

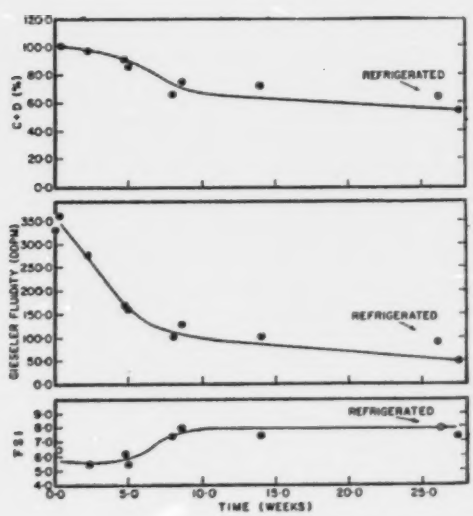

Fig. 39 - Thermal rheological properties of a western Canadian mvb coal vs storage time

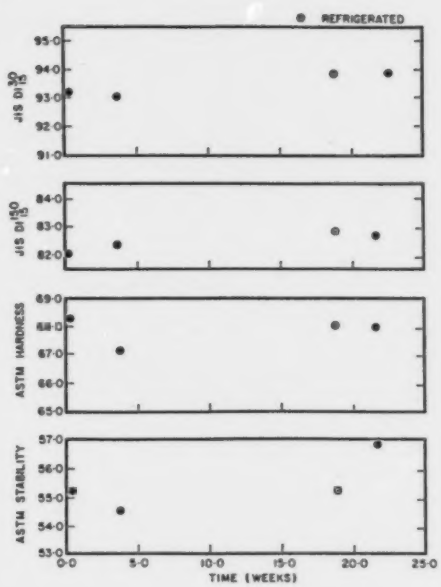

Fig. 40 - Coke strength parameters vs coal storage time

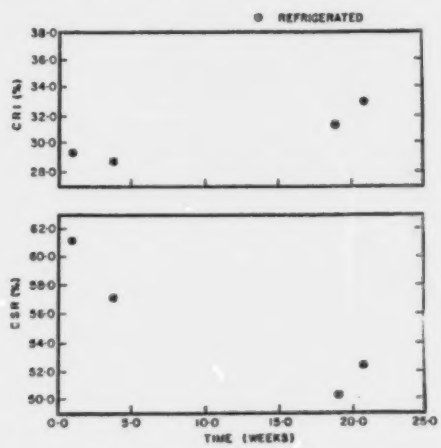

Fig. 41 - CRI and CSR vs coal storage time

For the coal in the above study, the deterioration in coal quality can be measured by the dilatation and fluidity properties of the coal. However, in many of the higher rank mvb and lvb coals from western Canada, dilatations and Gieseler fluidities can be low for freshly mined (good coking) coals, and alternative laboratory methods (other than a carbonization test) are required to determine if samples are deteriorating in storage. Nova Scotian hvAb coal has very large dilatation and Gieseler fluidity values, and oxidation of the coal can be readily detected by these thermal rheological methods. Stability of coke from this coal actually improves with partial oxidation because of the effective enhancement of the reactive to inert ratios (43).

During their investigation of thermal rheological properties, researchers at the University of Waterloo found that the Gieseler fluidity and Ruhr dilatation properties of western Canadian coals deteriorated slightly more rapidly under storage than Appalachian coals of similar rank. However, Figure 42 shows dilatation results from a CANMET investigation with a western Canadian coal and an Appalachian coal of similar rank (Ro's of 0.90 and 0.88, respectively) in which both coals deteriorated at very similar rates during storage at 20°C in air.

Several techniques in addition to thermal rheology have been used to determine oxidation of coal samples. These methods include phase inversion, flotation, pH of slurry, alkali solubility, and spectroscopic techniques (83). Spectroscopic techniques such as PASFTIR and NMR have also been successful in relating coal oxidation to chemical functional groups in the coals. These techniques have shown that carbonyl groups, in the form of carboxyl and possibly ketone or quinone functions, are introduced as well as phenolic groups in oxidized Canadian coals (84,85,86). However, for most Canadian coals these tests have been related to relatively gross changes in oxygen content associated with seam depth but have been of limited use for stockpiled samples that have undergone relatively mild oxidation (87). It is well established that the temperature at which coal oxidation occurs affects the nature of oxidation products (88). Mikula and Axelson found almost no changes could be observed in the FTIR or NMR spectra of western Canadian coal samples oxidized in stock-piles or under relatively mild laboratory conditions, even though relatively large changes in coke quality could be observed. However, dipolar dephasing nmr experiments did show that mild oxidation or weathering had resulted in some reduced molecular mobility in the coal (89).

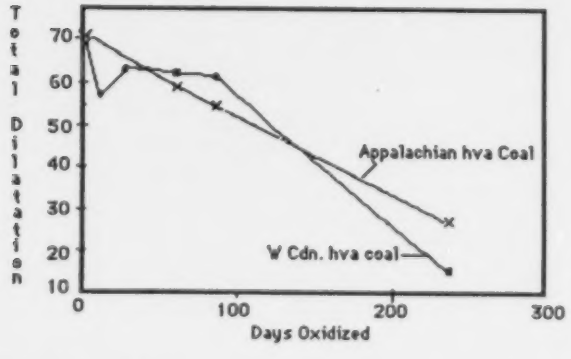

Fig. 42 - Effect of storage in air at ambient temperatures on the total dilatation of hvA coals from Appalachia and western Canada

There is also concern among some coal producers in western Canada that it is difficult to distinguish between naturally oxidized coal and good coking coal in their operations using thermal rheological methods because even good coking coals often have low thermal rheological properties. The alkali solubility test proved useful for one western Canadian coal producer to distinguish if a coal could be cleaned in their wash plant. Other tests such as the phase inversion test, or ΔP, could prove to be quick methods to distinguish between oxidized and unoxidized coals without reverting to spectroscopic or analytical chemistry techniques (87,89). CANMET is currently investigating these and alternative methods for examining oxidation in Canadian coals.

DISCUSSION AND SUMMARY

In 1986, Canada exported about 21.5 million tonnes of coking coal, which represents over 80% of Canada's coal exports. Canada's coking coal reserves are 2030 megatonnes of recoverable coal and are located in Alberta, British Columbia, and Nova Scotia. The metallurgical coal reserves of Nova Scotia (133 megatonnes) are of carboniferous age, while those from the Rocky Mountains of Alberta and British Columbia (1897 megatonnes) are mainly Cretaceous in origin. The Rocky Mountain coals have undergone quite different coalification than the carboniferous coals. Although there are exceptions, these coals have generally been formed in peat swamps under a nonmarine cover that maintained the acidic nature of the bog, and with periodic oxidizing conditions. Consequently, these coals have reduced volatile matter contents, with higher kaolinite, higher quartz, and reduced pyrite contents than eastern Canadian or Appalachian coals. The tertiary Laramide Orogeny metamorphosed the Rocky Mountain coals to the same rank as the carboniferous coals that are some 200 million years older, bringing seams closer to the surface but resulting in much folding and faulting that complicates mine planning. The geological history of most western Canadian coals makes them more friable than carboniferous coals. The higher fines contents generally make these coals more difficult to beneficiate, resulting in increased use of water-only washing cyclone circuitry for most western Canadian preparation plants.

THE QUALITY OF COKE FROM CANADA'S METALLURGICAL COALS

Coke must have two basic properties to be considered of high quality. It must be a relatively pure form of carbon and it must be of high strength so that it does not deteriorate during its passage through the blast furnace. Coke purity depends on the contents of ash and trace elements in the coal. Coke strength is primarily dependent on the rank and caking properties of the coal although other factors such as coal ash, pulverization, and carbonization methods can also influence coke strength at ambient temperatures. Recently, coke strength after reaction to CO_2 at 1100°C is being considered as a very important parameter to successful blast furnace operation and is dependent on the reactivity of the coke.

Canada has all types and ranks of bituminous coal that can be used individually or in blends to make high-quality coke. Nova Scotia has a hvA coal of economic significance, but the Rocky

Mountain coals in Alberta and British Columbia have all ranks of coking coals.

HvAb coal from Nova Scotia has low ash content and a high vitrinite content after preparation, but has too low a rank to make strong coke on its own. It is an excellent coal for blending because it has high caking properties and low ash content, and can be blended with numerous coals that have higher rank but are deficient in reactives. It is ideal for blending with the western Canadian coking coals that have higher rank, higher inert contents, higher ash levels, and lower sulphur levels. A blend of Nova Scotian coal with a lv coal from western Canada has been used at the Sydney Steel Corporation for some time. CANMET investigations of partial briquetting and preheating of coke oven charges show that the Nova Scotian coal, when carbonized alone, is particularly suited for use with preheating technology. Little improvement in coke quality resulted from partially briquetting Nova Scotian coal but improvements were observed when blended with low-volatile coal. Large quantities of non-coking materials such as chars, semi-anthracites, and petroleum cokes could be included in conventional and partially briquetted charges containing Nova Scotian coals to improve coke quality. Nova Scotian hvA coal can be used very successfully as a binder coal for chars or non-coking coals in hot-briquetting formed coke processes.

Coking coals from western Canada are mainly medium-volatile bituminous, although coals of all ranks are found as shown in Figure 21. Petrographically, the western Canadian coals are high in inerts, especially semifusinites. The coals can be carbonized individually or in blends with either other western Canadian coals or foreign coals to meet the ambient coke strength specifications demanded by world cokemakers. The coals generally have ash (mineral matter) contents that are consistent with blend averages of steel plants in Japan. These ash contents are considered high by Canadian steel manufacturers who use mainly Appalachian coking coals in their coking blends. Decreasing the ash (mineral matter) content of coals gives a significant improvement to coke stability when the coals are carbonized individually but a somewhat lower improvement when carbonized in blends with Appalachian coals. Small samples of western Canadian coals can be susceptible to oxidation and they should be tested immediately to measure optimum properties. This is particularly true for thermal rheological and CSR properties. ASTM stability may or may not deteriorate during the first few weeks of storage depending on the coal used.

Coke strength after reaction (CSR) properties of the western Canadian coals and blends are excellent, and CANMET studies comparing cokes made from blends of western Canadian coals with blends made from U.S. Appalachian coals are consistent with results shown in Figure 43, reported by the Nippon Steel Corporation (20). In spite of slightly higher ash contents, analysis of CANMET data shows that the very good CSR and CRI results from western Canadian coals are probably attributable to the low basicity and low concentrations of elements such as Fe, Na, K, Mg, and Ca in the ash, which are known to catalyze coke reactivity and to be detrimental to coke quality (26). Also, the coals are mostly medium- to low-volatile in rank, considered optimum for CSR properties.

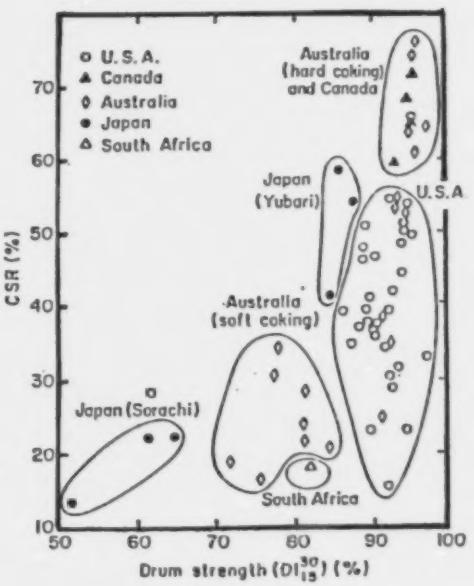

Fig. 43 - Relation between coke strength and CSR properties showing the high quality of hard coking coals from Canada (after Ishikawa et al. 1983)

Carbonization conditions used for Canadian coals have been shown in CANMET investigations to have a significant influence on CSR and other coke strength properties. Increased coking rate improves the CSR properties of all coals significantly (including western Canadian) but is detrimental to ASTM stability (47,90). Finer pulverization of western Canadian coal improved ASTM stability by about 2-4 units for every 10% increase in the amount of coal passing a 3 mm sieve (91). Coke quality from western Canadian good coking coals is particularly sensitive to changes in bulk density, and as a result these coals are suited for use in high-density charging techniques such as partial briquetting and, to a lesser extent, preheating of coal charges.

Pitch additives can be used to make high-quality cokes from weak and non-coking western Canadian coals. Certain pitch materials can enhance the caking properties of weak coking coals and, when used with conventional or partially briquetted coke oven charging practices, will make cokes with very good strength and CSR properties, provided the rank of the coal or blend meets blending specifications. Coking and non-coking western Canadian coals can be used in formed coke processes, particularly those using pitch, or in binderless briquetting technology.

Thermal rheological and petrographic properties of Nova Scotian and Appalachian coals generally have much larger Gieseler fluidities and Ruhr dilatation properties than the cretaceous western Canadian coals. Gieseler fluidity and Ruhr dilatation tests are less reliable for predicting coke quality of many low-caking western Canadian coals than FSI, since the former tests cannot always distinguish good from poor coking coals. Eastern North American coals have higher vitrinite, exinite, and micrinite levels than the western Canadian coals, which have higher semifusinite contents. Investigations have shown that differences in the dilatations of Appalachian and western Canadian coals cannot be attributed entirely to differences in particle size, coal maceral composition, and/or microlithotype composition and must be attributed in part to inherent differences in the vitrinite of the coal types. Although western Canadian coals have lower apparent caking properties, a microscopic study of the coal to coke transformation in a western Canadian and Appalachian coal of the same rank showed the western Canadian coal had a larger melting range than the Appalachian coal (81). Gieseler fluidity and petrographic studies by Sunami have shown that purified vitrinites from different types of coal of the same rank can have quite different Gieseler fluidities and different optimum reactives/inert ratios (ORI). Sunami has developed a modified method of calculating optimum reactive/inert in petrographic predictions of coke strength by including the fluidity of the pure vitrinite. The method has the effect of lowering the composition balance index (CBI) for high inert western Canadian coals, resulting in higher and more realistic predictions of coke strength. The reactivity of semifusinite in western Canadian coals is still being investigated at CANMET using both petrographic and coke microscopy techniques. Petrographic studies using a method of back calculating the effective reactive semifusinite from test oven stabilities showed that the effective amount of reactive semifusinite is dependent on the rank of the coal and amount of low reflecting semifusinite in the coal. Investigations using coke microscopy to identify the actual inerts remaining in the coke may give better estimates of the true ratio of reactive/inert semifusinites.

Coking pressure created by coals during carbonization is also of critical concern to cokemakers around the world. With the policy of using fast coking rates in batteries greater than 5 m tall, the possibility of damage to the oven walls caused by excessive carbonization pressure in the coal charge has become a reality. U.S. Steel (Fairfield and Gary Works), Inland Steel (Chicago), Bethelehem Steel (Burns Harbour), and British Steel (Red Car) have all had one or more batteries showing refractory failures caused by excessive coking pressures (31). Coking pressure generally increases with coal rank. The Nova Scotian hv coal exhibits little or no coking pressures because of its rank, but many medium- and low-volatile carboniferous coals can give high coking pressures. Coking investigations, described previously in this report, showed that single coals or blends containing medium- or low-volatile western Canadian coals generally had lower coking pressures than blends containing only Appalachian coals. In a study reported elsewhere, the substitution of a Canadian mv coal for an Australian mv coal in an Australian (mv)/U.S.A. (lv)/ U.K. (lv) blend had the effect of reducing the coking pressures from an unacceptable pressure to an acceptable value (31,92). The high inert and lower caking properties of the vitrinite in the western Canadian coals have the effect of reducing coking pressures.

In industrial trials recently carried out by Algoma Steel Corporation, a mv western Canadian coal was added to their binary hv/lv Appalachian coal blend. No coal handling, coke oven pushing, or other operational problems were encountered when the western Canadian coal was used, and the company concluded that the western Canadian coal served as a good bridging coal in their blend and reduced coking pressures. The blend containing the mv coal improved CSR properties while maintaining the ASTM stability of the original blend.

OTHER POTENTIAL USES FOR CANADIAN METALLURGICAL COALS

Canada has an abundance of non-coking coals that can be used for other metallurgical purposes. For example, the anthracite deposits in northern British Columbia could be used as a reductant and energy source in processes for phosphorus, titanium, and BOS steel production (93). The dramatic changes in the energy market in recent years have caused metallurgists to develop new iron and steelmaking process concepts more suited to the future energy situation.

Pulverized Coal Injection (PCI) into the blast furnace is being used increasingly in North America, Japan, and Europe. PCI can replace between 0.8 to 1.1 kg of coke for every kg of coal injected with the higher replacement ratio achieved at lower ash content of the coal. The hydrogen content of injectant influences the flame temperature because of the endothermic nature of the reaction to form hydrogen gas and to some extent controls the amount of coal that can be injected. Hydrogen content in coal is controlled by rank and moisture content. The Chinese have achieved quite high injection rates (up to 25% of the fuel) using anthracite coals, which have low hydrogen contents (94). On the other hand, more complete coal burnoff can be achieved with coals containing higher volatile matter (95) and PCI has been successful using coals with ranks from lignite to anthracite (96). National Steel recommends injecting soft coals with low ash, high ash basicity, and low ash fusion to improve slag chemistry and minimize tuyere failures (97). The introduction of PCI in blast furnaces cannot eliminate the use of coke in the blast furnace and, may increase demand for better quality of coke and other blast furnace burden materials to ensure successful blast furnace operation (97).

New direct ironmaking and steelmaking processes such as the KR process (98), the CGS coal gasification process (99), the Krupp COIN process (100), and McMaster University's-LB process (101) will influence new potential uses for Canadian coals.

CONCLUSIONS

Coking coals from western Canada are mainly medium-volatile bituminous in rank, although mines are producing both high- and low-volatile bituminous coals. Although there are exceptions to the following, the coals produced generally:

- are friable, which causes some special considerations in mine planning, preparation plant design, coal handling, storage, and testing;
- are high in inherent mineral matter content but have low basicity of the ash;
- have very low sulphur contents;
- make strong coke suitable for blast furnace use individually, or in blends with Nova Scotian or foreign coals;
- have high semifusinite contents, making estimates of reactive/inert ratios and predictions of coke quality often inaccurate from standard petrographic procedures;
- do not respond to Gieseler and dilatation test methods, causing coke quality predictive models to underrate many of these coals;
- are compatible and complementary in ash, sulphur, and caking properties to coking coals from eastern North America and many foreign coals;
- provide adequate bridging to binary blends of high- and low-volatile coals during the melting phase;
- reduce coking pressure when added to highly expanding coals or blends;
- are sensitive to coking conditions such as coking rate, coal bulk density, and coal pulverization levels;
- are particularly useful with technologies utilizing high density charging, e.g. partial briquetting because of the large improvements associated with higher bulk densities;
- produce cokes either individually or in blends with low reactivity and excellent CSR values as a result of their rank and low basicity of their ash.

Weak and non-coking coals from western Canada can be used in conventional, partial briquetting, or form coke processes using pitch binder. The pitch enhances the caking properties of these coals and improves coke properties. Laboratory work at CANMET has also shown that strong formed coke can be made by carbonizing briquets made from oxidized western Canadian coals without the use of binder.

Coking coal from Nova Scotia is good for blending purposes in conventional cokemaking:

- it is hvA bituminous in rank;
- it has a high vitrinite content, very high fluidity and dilatation properties, and is ideal for blending with high inert coals of higher rank;
- the coal has very low ash content but a slightly high sulphur content;
- the coal can be used in preheating and partial briquetting processes but is more suited for use in the former technology;
- large quantities of chars or petroleum cokes can be incorporated into coking blends containing this coal to make strong coke;
- the high fluidity of the coal makes it a very good binder coal in formed coke processes using hot-briquetting technology.

The changing energy scene in new iron, steel, and other metallurgical processes presents challenges and opportunities to extend the use of Canadian metallurgical coals.

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APPENDIX A

COKING COAL MINE OPERATORS

Mine Operator & Head Office	Mine Name, Location	Basic Mine Type	1985 Mine Output 1000 T	No. of employees	Major Markets
Nova Scotia					
Sydney Coalfield					
Cape Breton Development Corp. P.O Box 2500 Sydney, N.S. B1P 6K9	Lingan Colliery Lingan Nova Scotia P. Jones - Colliery General Manager	underground	1633	staff: 80 others: 1115	metallurgical coal for local & export markets;
Alberta's Mountain Region					
Cadomin-Luscar Coalfield					
Cardinal River Coals Ltd. 1600 Oxford Tower Edmonton, Alberta T5J 3G1	Luscar Mine Hinton, Alberta W. Bish General Manager	surface	1718	staff: 76 others:264	metallurgical coal primarily for export market
Gregg River Resources Ltd. c/o Manalta Coal Ltd. P.O. Box 2880 Calgary, Alberta T2P 2M7	Gregg Rive Mine Hinton, Alberta B. Payne Acting Mine Manager	surface	2135 met	staff: 100 hourly: 300	metallurgical coal for export market
Smoky River Coalfield					
Smoky River Coals Ltd. P.O. Box 2000 Grande Cache, Alberta TOE OYO	No. 9 Mine/Mine 1774 Grande Cache, Alberta K. Zehr General Manager	surface	686	Total staff: 105 hourly: 219	metallurgical and thermal coal for Canadian and Export markets.
	Mines 1765/09/B&G (as above)	underground	487	(as above)	(as above)

Coal Rank and Seams	Mining Method & Major Equipment	Coal Preparation Facilities	Remarks
high-volatile A bituminous; Harbour Seam; 2.1 m thick; dips 9° but varies from 5°to 10° seaward	Submarine, advancing longwalls; 3 shearer faces with powered roof supports; 6 roadway cutter loaders 3 ranging arm double drum shearers	Victoria Junction Preparation Plant coal crushed to -38 mm with +28 mesh processed thru heavy medium cyclones and -28 mesh in froth flotation cells; in addition to met. coal, plant produces a middling product for thermal	3 advancing long-walls operating. Phalen Mine on Phalen seam will begin operation mid 1987.
medium-volatile bituminous; Jewel Seam approx. 10-14 m thick but varies with folding; minor rider seams present; dip variable because of folding	shovel truck stripping 1 power shovel 23.0 m 4 power shovels 11.5 m 1 dragline(for coal) 3.8 m 18 haulage trucks 154 tonnes 17 haulage trucks 91 tonnes 5 rotary drills 9 bulldozers	prep. plant (1970, major expansion 1980) has coarse fraction washed in heavy medium cyclones; fine fraction treated in compound water cyclones, screens and froth flotation cells; coal dried in coal-fired fluid bed dryers; feed capacity 725 tonnes/h	
medium-volatile bituminous; Jewel Seam 10 m thick with thickening in synclinal troughs; dip variable	shovel truck stripping 2 hydraulic excavator 15 m3 1 power shovels 23 m3 2 frontend loaders 14 m3 8 haulage trucks 154 tonnes 6 haulage trucks 109 tonnes 7 bulldozers	in prep. plant (1983) coarse fraction washed in heavy medium bath; medium fraction cleaned in heavy medium cyclones and fine fraction in compound water cyclones; coal dried in coal dried fluid bed dryer. Feed capacity 450 tonnes/h.	
low-volatile bituminous; Seam #4 (average 6 m thick but structurally thickened to 30 m); Seam #10(3 m thick- minor portion of production); Seam #11(2 to 3 m thick- not mined)	shovel truck stripping; 4 power shovels 11.5 m3 13 haulage trucks 134 tonnes 7 haulage trucks 75 tonnes 5 coal trucks 45 3 frontend loaders 10 m3 4 rotary drills 7 bulldozers 1 backhoe 2.5 m3	preparation plant (1969) has coarse fraction cleaned in heavy medium cyclones; fine fraction cleaned in froth flotation cells; coal product dried in natural gas fired fluid bed dryer; feed capacity 590 tonnes/h; reject and dewatered tailings go to adjacent utility plant.	
Seam #4 as above; dip varies from near level to 14°(average 6 m thick)	room and pillar; 4 continuous miners 8 shuttle cars 5 roof bolters 3 load-haul-dumps	(as above)	

Mine Operator & Head Office	Mine Name, Location	Basic Mine Type	1985 Mine Output 1000 T	No. of employees	Major Markets
British Columbia					
Crowsnest Coalfield					
Byron Creek Collieries c/o Esso Resources Canada Ltd. 237-4th Ave. S.W. Calgary, Alberta T2P OH6	Coal Mountain Mine (formerly Corbin Mine) Sparwood, B.C.	surface	1146	staff:64 others:135	"weak" coking coal for export Thermal coal for Ontario and export markets
Westar Mining Ltd. 1176 W. Georgia St. Vancouver, B. C. V6E 4B8	Harmer Surface Mine Sparwood, B.C. John Powell General Manager	surface	5676	staff:165 others: 875	metallurgical coal for export
Elk Valley Coalfield					
Fording Coal Ltd. 200, 205 9th Ave. S.E. Calgary, Alberta T2G OR4	Fording River Mine Elkford, B.C. D. L. Gaspe General Manager	surface	5177	staff: 105 others: 1080	metallurgical and thermal coal for domestic and export markets.
Westar Mining 1176 W. Georgia St. Vancouver, B.C. V6E 4B8	Greenhills Mine Elkford, B.C. S. Oishi General Manager	surface	1264	staff: 95 others: 225	primarily met. coal for export market as well as thermal coal for export.
Crows Nest Resources Ltd. c/o Shell Canada Resources 525 Third Ave. S.W. T2P 2M7	Line Creek Mine Sparwood, B. C R.A. Rouleau- President	surface	2300	staff: 107 others: 340	metallurgical and thermal coal export markets

Coal Rank and Seams	Mining Method & Major Equipment	Coal Preparation Facilities	Remarks
medium-volatile bituminous; No. 1 Seam has highly variable thickness from a few metres up to some 60 m and higher in certain faulted and folded areas.	shovel-truck stripping; 1 hydraulic shovel 14.5 m3 4 frontend loaders 9 m3 2 frontend loaders 6 m3 13 haulage trucks 77 tonnes 5 haulage trucks 109 tonnes 5 haulage trucks 32 tonnes 2 rotary drills 6 bulldozers	Jig Plant- in preparation plant (1978) coarse and fine coal fractions are separated, coarse coal cleaned in a five-cell jig, dewatered, recombined with fine coal; dried mechanically feed capacity 330 tonnes/h. Heavy Media Plant- completed in 1986, coarse coal cleaned in heavy media cyclone and fine coal is cleaned in two-stage water only cyclones. Product coal is dried in a gas-fired thermal drier. Feed capacity 450 tonnes/h.	
low- to medium-volatile bituminous; essentially one seam called 10 seam; thickness from 12 to 15 m; dip varies from 18° to 55° but mostly in range of 20°.	shovel-truck stripping; 4 power shovels 19 m3 4 power shovels 11 m3 1 power shovel 23 m3 22 haulage trucks 180 tonnes 23 haulage trucks 154 tonnes 18 haulage trucks 90 tonnes 1 haulage truck 320 tonnes 9 rotary drills 1 frontend loader 27 m3 4 frontend loaders 17 m3 12 bulldozers	Elkview Coal Prep. Plant (1970, expanded in 1972) has two streams; coarse coal cleaned in heavy medium vessels and middle-sized fraction in heavy medium cyclones; fine coal cleaned in two stages of water cyclones, vibrating sieve bands and froth flotation cells; fine coal dried in fluid bed dryer; feed capacity 1,600 tonnes/h.	prior to June, 1983 Westar Mining Ltd was named B.C. Coal Ltd., prior to Oct. 1980, B.C Coal Ltd. was named Kaiser Resources Ltd.
low-, medium- and high-volatile bituminous; up to 11 seams mined ranging in thickness from 1.5-11 m; dip varies with regional structures but generally in the range 20° to 25°	truck shovel mining on both Eagle Mountain and Greenhills sides plus dragline mining on Greenhills side 5 shovels 23 m3 4 shovels 11.5 m3 1 dragline 45.8 m3 23 bulldozers 40 haulage trucks 154 tonnes 19 haulage trucks 108 tonnes 6 frontend loaders 11.5 m3 9 rotary drills 7 graders 6 scrapers/waterboys	prep. plant (1972) has two streams; coarse coal cleaned in vertical wheel separators and middle-sized fraction in heavy medium cyclones; fine coal has water only cyclones and froth flotation cells; clean coal dryer is coal-fired; feed capacity 1200 tonnes/h.	
medium- and high-volatile bituminous coal of some 14 seams, in mine area Seams Nos. 1,7,10 & 16 provide 80% of recoverable coal and range in thickness from 5-11m; dip varies in synclinal structures from 20° to 60°.	shovel truck stripping 3 hydraulic shovels 14 m3 2 frontend loaders 21 m3 1 frontend loader 17 m3 1 frontend loader 10 m3 14 haulage trucks 90 tonnes 3 rotary drills 4 bulldozers	prep. plant (1983) has two streams: coarse coal cleaned in heavy medium cyclones; fine size cleaned in two-stage water only cyclones, two-stage sieve bands and froth flotation cells; clean coal dryers are gas-fired; feed capacity currently approx. 500 tonnes/h.	prior to June 1983 Westar Mining Ltd. was named B.C. Coal Ltd., prior to Oct. 1980, B.C. Coal Ltd. was named Kaiser Resources Ltd.
low- and medium-volatile bituminous; four of 7 seams in mine area have 90% of reserves; thickness 3 m to 13 m; dips range 35° to 45°.	shovel truck stripping; 2 power shovels 11.5 m3 1 power shovel 14 m3 2 hydraulic excavators 3.4 m3 2 hydraulic excavator 8.4 m3 2 frontend loaders 11.5 m3 2 frontend loaders 6.1 m3 4 rotary drills 2 haulage trucks 118 tonnes 7 haulage trucks 109 tonnes 10 haulage trucks 77 tonnes 10 haulage trucks 40 tonnes 9 bulldozers	separate met. and thermal coal prep. plants. in met. prep. plant coarse fraction treated in heavy medium cyclones; fine coal cleaned in two stage water cyclones and froth flotation cells; clean coal dryer is gas fired; feed capacity 375 tonnes/ h. in thermal prep. plant coarse fraction is dry screened then cleaned in two-product heavy medium bath; coarse coal is mechanically dewatered; fine coal is bypassed to product ; feed capacity 275 tonnes/h.	

Mine Operator & Head Office	Mine Name, Location	Basic Mine Type	1985 Mine Output 1000 T	No. of employees	Major Markets
Peace River Coalfield					
Teck Corporation 1199 W. Hastings St. Vancouver, B. C. V6E 2K5	Bullmoose Mine Tumbler Ridge, B.C. F. Koch Mine Manager	surface	1700	approx. 420	metallurgical and thermal coal export markets
Denison Mines Ltd. Coal Division 650 W. Georgia St. Vancouver, B.C. V6B 4N7	Quinette Mine Tumbler Ridge, B.C. J. Sanders Mine Manager	surface	5300	approx. 1400	metallurgical and thermal coal export markets

Coal Rank and Seams	Mining Method & Major Equipment	Coal Preparation Facilities	Remarks
medium-volatile bituminous; five seams with thickness between 1.4 m and 4.8 m, totalling about 13 m; dip 5° to 7°	shovel-truck stripping; 4 power shovels 12.6 m3 2 hydraulic excavators 12.0 m3 19 haulage trucks 120 tonnes 4 haulage trucks 154 tonnes 1 frontend loader 9 m3 2 frontend loaders 11 m3 2 frontend loaders 4 m3 6 bulldozers 3 rotary drills	in prep. plant (1983) coarse coal fraction is cleaned in heavy medium cyclones; fine coal fraction has 3 stages of cleaning utilizing two stage water cyclones and froth flotation cells; clean coal is dried in coal-fired fluid bed dryer; feed capacity 450 tonnes/h.	production started in 1983
medium-volatile bituminous; between four and six seams to be mined in various pits with aggregate thickness between 17 m & 19 m; dips within synclinal folds in range 15° to 30°.	shovel-truck stripping; 8 power shovels 23 m3 3 hydraulic shovels 14 m3 3 frontend loaders 11 m3 14 haulage trucks 154 tonnes 5 haulage trucks 77 tonnes 7 drills 11 bulldozers	prep. plant (1983) has two met. coal circuits each of 600 tonnes/h feed capacity and one thermal coal circuit of 350 tonnes/h feed capacity; four cleaning process used; heavy medium drum, heavy medium cyclones, water-only washing cyclones and froth flotation cells.	production started in 1983

APPENDIX B

TYPICAL ANALYSES OF METALLURGICAL COAL PRODUCTS FROM CANADIAN MINES

Byron Creek Collieries Ltd.
Corbin Mine,
Corbin, British Columbia

Product		Byron Creek coal
Rank of Coal (ASTM)		mvb
Proximate Analysis		
Moisture		8.0
Ash	% (db)	8.95
Volatile matter	% (db)	25.1
Fixed carbon	% (db)	65.95
Calorific Value MJ/kg (as received)		29.6
	% (db)	32.2
Ultimate Analysis	% (db)	
Carbon		77.5
Hydrogen		4.33
Sulphur		0.30
Nitrogen		0.71
Ash		8.7
Oxygen (by difference)		8.4
Ash Fusibility Temperature:J°C		
Initial		1430.
Spherical		
Hemispherical		1480.+
Fluid		1480.+
Grindability Index (Hardgrove)		78.
Free Swelling Index (ASTM)		3-5.

Ash analysis

SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
48.2	33.5	2.5	- -	2.2	1.0	5.7	1.2	3.6	1.0	0.5

Bullmoose Operating Ltd.
Bullmoose Mine
Tumbler Ridge, B. C.

Product		Bullmoose Clean Coal
Rank of Coal (ASTM)		mvb
Proximate Analysis		
Moisture as shipped	%	8.0
Ash	% (db)	9.22
Volatile matter	% (db)	26.55
Fixed carbon	% (db)	64.23
Calorific Value MJ/kg		32.31
Ultimate Analysis	% (db)	
Carbon		79.54
Hydrogen		4.68
Sulphur		0.33
Nitrogen		1.03
Ash		9.26
Oxygen (by difference)		5.14
Ash Fusibility Temperature: °C		
Initial		1195.
Spherical		1243.
Hemispherical		1271.
Fluid		1321.
Grindability Index (Hardgrove)		73.
Free Swelling Index (ASTM)		5.5

Ash analysis

SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
49.3	20.65	3.92	- -	1.76	1.48	7.43	3.13	5.88	0.90	0.66

Cardinal River Coals Ltd.
Cardinal River Mine; Jewell Seam
Mountain Park Coalfield, Hinton, Alberta

Product		Clean Coal
		1985
Rank of Coal (ASTM)		mvb
Proximate Analysis	% as shipped	
Moisture		7.8
Ash		8.8
Volatile matter		21.1
Fixed carbon		62.3
Calorific Value MJ/kg		
Ultimate Analysis	% (db)	
Carbon		80.1
Hydrogen		4.5
Sulphur		0.30
Nitrogen		1.2
Ash		9.5
Oxygen (by difference)		4.4
Ash Fusibility Temperature:	°C	
Initial		
Spherical		
Hemispherical		1430.+
Fluid		1480.+
Grindability Index (Hardgrove)		80.
Free Swelling Index (ASTM)		7.

Ash analysis

	SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
2947-77	51.8	26.0	3.8	- -	1.4	0.7	5.8	1.4	4.8	1.2	0.4

Cape Breton Development Corporation (DEVCO)
Lingan Mine; Harbour Seam; Sydney Coalfield
Lingan, Cape Breton County, Nova Scotia

Product		Coal Preparation Plant
Rank of Coal (ASTM)		mvb
Proximate Analysis		
Moisture as shipped	%	8.0
Ash	% (db)	3.5
Volatile matter	% (db)	36.5
Fixed carbon	% (db)	60.
Calorific Value MJ/kg	% (air dry)	34.2
	% (db)	34.7
Ultimate Analysis (daf basis)	%	
Carbon		86.8
Hydrogen		5.7
Sulphur		1.2
Nitrogen		1.3
Chlorine		0.1
Oxygen (by difference)		5.0
Ash Fusibility Temperature °C:		
Initial		1110.
Spherical		1150.
Hemispherical		1205.
Fluid		1310.
Grindability Index (Hardgrove)		65.
Free Swelling Index (ASTM)		7.5

Ash analysis

SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
32.	18.	42.	-	0.9	0.3	1.7	0.8	1.5	0.9	1.0

Fording Coal Ltd.
Fording River Mine
Elk Valley Coalfield
Elkford, British Columbia

Product		Clean Coal	Clean Coal	Clean Coal
ERL Laboratory No		0106-84	0106-85	0106-86
Rank of Coal (ASTM)		hvAb	mvb	mvb
Proximate Analysis				
Moisture				
Ash	% (db)	5.8	7.7	9.8
Volatile matter	% (db)	32.3	28.0	21.1
Fixed carbon	% (db)	61.9	64.3	69.0
Calorific Value MJ/kg (as received)				
	% (db)	33.2	33.0	32.3
	% (daf)	35.2	35.7	35.8
Ultimate Analysis	% (db)			
Carbon		81.2	80.4	80.7
Hydrogen		4.7	4.5	4.0
Sulphur		0.44	0.75	0.31
Nitrogen		1.5	1.5	1.0
Ash		5.8	7.7	9.8
Oxygen (by difference)		6.4	5.1	4.2
Ash Fusibility Temperature: °C		Reducing		
Initial		1463.	1474.	1482.+
Spherical		1482.+	1482.+	1482.+
Hemispherical		1482.+	1482.+	1482.+
Fluid		1482.+	1482.+	1482.+
Grindability Index (Hardgrove)				
Free Swelling Index (ASTM)		8.0	8.0	

Ash analysis

ERL Lab No.	SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
0106-84	58.4	27.6	4.7	-	1.6	1.1	1.8	0.6	1.1	0.1	1.2
0106-85	57.5	28.8	3.9	-	1.6	1.9	1.9	0.4	1.0	0.1	1.2
0106-86	57.7	32.6	3.8	-	1.7	0.9	1.4	0.3	0.6	-	0.3

Crowsnest Resources Ltd.
Line Creek Mine
Sparwood, B. C.

Product		Line Creek Metallurgical Coal (Preparation Plant)
ERL Laboratory No		3622-85
Rank of Coal (ASTM)		mvb
Proximate Analysis		
Moisture		
Ash	% (db)	9.5
Volatile matter	% (db)	21.6
Fixed carbon	% (db)	69.1
Calorific Value MJ/kg		32.85
Ultimate Analysis (db)		
Carbon		80.9
Hydrogen		4.4
Sulphur		0.4
Nitrogen		1.5
Ash		9.3
Oxygen (by difference)		3.5
Ash Fusibility Temperature:		
Initial	°C	1482.+
Spherical		1482.+
Hemispherical		1482.+
Fluid		1482.+
Grindability Index (Hardgrove)		78.
Free Swelling Index (ASTM)		6.5

Ash analysis

SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
59.1	29.3	3.0	- -	2.0	1.2	1.4	0.3	0.4	0.1	0.5

Gregg River Resources Ltd.
Hinton, Alberta

Product		Metallurgical Coal Product
Rank of Coal (ASTM)		mvb
Proximate Analysis		
Moisture	%	8.0
Ash	% (db)	9.5
Volatile matter	% (db)	25.2
Fixed carbon	% (db)	65.3
Calorific Value MJ/kg	(db)	33.15
Ultimate Analysis	% (db)	
Carbon		79.5
Hydrogen		4.47
Sulphur		0.33
Nitrogen		1.16
Ash		9.5
Oxygen (by difference)		5.07
Ash Fusibility Temperature	°C	
Initial		
Spherical		
Hemispherical		
Fluid		
Grindability Index (Hardgrove)		89.
Free Swelling Index (ASTM)		5.5

Ash analysis

SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	P_2O_5	CaO	MgO	SO_3	(Na_2O+K_2O)
55.65	28.0	4.98	--	1.03	0.63	3.86	1.04	2.44	1.83

analyses provided by Gregg River Resources Ltd.

Quintette Coal Ltd.
Quintette Coal Mine,
Tumbler Ridge, B.C.

Product		Typical Clean Coal Product*
		1985
Rank of Coal (ASTM)		mvb
Proximate Analysis	%	
Moisture as shipped		8.0
Ash		8.7
Volatile matter		22.
Fixed carbon		61.3
Calorific Value MJ/kg	(db)	32.8
Ultimate Analysis	% (db)	
Carbon		79.5
Hydrogen		4.5
Sulphur		0.4
Nitrogen		1.0
Ash		9.5
Oxygen (by difference)		5.1
Ash Fusibility Temperature:	°C Reducing	
Initial		1320.
Spherical		1364.
Hemispherical		1395.
Fluid		1437.
Grindability Index (Hardgrove)		75- 80.
Free Swelling Index (ASTM)		6-7.

Ash analysis

SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
55.-65	20-25.	3.-6.	--	1.-2.	0.5-1	3.-6.	1.-2.	3.-4	0-1.	1-1.5

*analyses provided by Quintette Coal Ltd.

Smoky River Coal Ltd.
Grande Cache, Alberta

Product		Metallurgical Coal
ERL Laboratory		No 0105-94
Rank of Coal (ASTM)		1vb
Proximate Analysis		
Moisture		
Ash	% (db)	7.2
Volatile matter	% (db)	17.4
Fixed carbon	% (db)	75.4
Calorific Value MJ/kg	(db)	34.0
Ultimate Analysis	%(db)	
Carbon		85.7
Hydrogen		4.1
Sulphur		0.38
Nitrogen		1.1
Ash		7.2
Oxygen (by difference)		1.5
Ash Fusibility Temperatures:	°C	
Initial		1429.
Spherical		1482.+
Hemispherical		1482.+
Fluid		1482.+
Grindability Index (Hardgrove)		93.
Free Swelling Index (ASTM)		5.5

Ash analysis

SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
53.0	27.9	4.5	- -	1.8	1.3	4.3	0.4	2.8	1.1	0.2

Westar Mining Ltd.
Greenhills Mine; Elk Valley Coalfield
Elkford, B.C.

Product		Clean Coal, Preparation plant
ERL Laboratory No		3933-84
Rank of Coal (ASTM)		mvb
Proximate Analysis		
Moisture		
Ash	% (db)	6.43
Volatile matter	% (db)	27.39
Fixed carbon	% (db)	66.18
Calorific Value MJ/kg	(as received)	32.1
	% (db)	33.2
	% (daf)	35.5
Ultimate Analysis	% (db)	
Carbon		81.64
Hydrogen		4.68
Sulphur		0.47
Nitrogen		1.62
Ash		6.43
Oxygen (by difference)		5.16
Ash Fusibility Temperature: °C	Reducing	
Initial		1482.+
Spherical		1482.+
Hemispherical		1482.+
Fluid		1482.+
Grindability Index (Hardgrove)		86.
Free Swelling Index (ASTM)		6.0

Ash analysis

SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
52.97	29.4	4.89	- -	1.84	2.81	3.05	0.64	0.93	0.09	0.74

Westar Mining Ltd.
Michel Mine
Sparwood, B.C.

Product		Clean Coal, Preparation plant
ERL Laboratory No.		2079-85
Rank of Coal (ASTM)		mvb
Proximate Analysis		
Moisture	%	8.0
Ash	% (db)	9.95
Volatile matter	% (db)	21.13
Fixed carbon	% (db)	68.92
Calorific Value	MJ/kg (as received)	30.98
	% (db)	32.43
	% (daf)	36.02
Ultimate Analysis	% (db)	
Carbon		81.73
Hydrogen		4.44
Sulphur		0.27
Nitrogen		1.38
Ash		9.95
Oxygen (by difference)		2.23
Ash Fusibility Temperature: °C	Reducing	
Initial		1482.+
Spherical		1482.+
Hemispherical		1482.+
Fluid		1482.+
Grindability Index (Hardgrove)		86.
Free Swelling Index (ASTM)		6.

Ash analysis

SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
60.41	27.69	2.70	- -	1.58	0.53	1.89	0.4	1.0	0.12	0.29